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An Initial Study of the Application of the Numerical Method of Characteristics to Unsteady Flow Analysis in Partially Filled Gravity Drainage Sized Pipes

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
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Summary

The application of the numerical method of characteristics to the solution of the differential equations defining unsteady flow in partially filled drainage system sized pipes is outlined.

The derivation of the flow equations is presented, together with the necessary boundary equation formulation to represent variable inflow, system discharge and leakage flow past a stationary deposited solid.

A computer program, written in Fortran, is included, together with typical output, that establishes the applicability of this computational method to unsteady flow analysis in gravity flow drainage systems.

Proposals for the extension of the described techniques to the prediction of solid transport and flow attenuation in long pipes are also presented.

Preface

This report is one of a group documenting National Bureau of Standards (NBS) research and analysis efforts in developing water conservation test methods, analysis, economics, and strategies for implementation and acceptance. This work is sponsored by the Department of Housing and Urban Development/Office of Policy Development and Research, Division of Energy Building Technology and Standards, under HUD Interagency Agreement H-48-78.

Report prepared by Dr. J. A. Swaffield, Senior Lecturer, Drainage Research Group, Department of Building Technology, Brunel University, Uxbridge, UK., during a study leave period as a guest research worker at NBS/Stevens Institute of Technology.

Experimental results included in this report are drawn from the published work of the Drainage Research Group at Brunel University.

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Notation

A	Pipe flow cross section area
C^+,C^-	Notation referring to the positive and negative characteristics
c	Wave speed
Fr	Froude No = $V/\sqrt{gh}$
g	Acceleration due to gravity
h	Flow depth
K	Coefficient in solid leakage characteristics, $Q = K(SE-SE_o)^2$
m	Hydraulic mean depth
N,n	No of pipe length sections employed
P	Wetted channel perimeter
Q	Flow rate
SE	Specific energy = $h + V^2/2g$
SE_o	Minimum specific energy required to initiate flow past solid
S_o	Pipe slope
S	Slope of energy grade line, defined by Manning's Equation
T	Surface width of flow within partially filled channel
t	Time
V	Local mean velocity
X1-4	Functions of h, V, c and S calculated at each base point at each time step
x	Distance, + ve in initial flow direction
α	Pipe slope, $S_o = \sin\alpha$
Δt	Time step
Δx	Pipe section length
Θ	$\Delta t/\Delta x$

λ	Multiplier in combination equation yielding total differential unsteady flow relationship = $\pm\sqrt{\frac{g}{AT}}$
ρ	Fluid density
τ_o	Wall to fluid shear stress

Suffixes

A, B, C	Calculated points in an x-t grid at time t
P	Calculated points in an x-t grid at time t + Δt
R, S	Interpolated points in an x-t grid at time t
U, D	Upstream and downstream conditions relative to the solid boundary

1. INTRODUCTION

Unsteady flow is defined as fluid flow wherein the flow parameters vary with time and as such will occur in all fluid carrying conduits if the system boundary conditions are rapidly changed, either by design or as a result of some unforeseen event. The rate of change of the system boundary conditions determine the severity of the flow parameter changes that result. In many cases the resulting pressures generated in the flow system determine the design conditions.

The most well documented area of transient analysis refers to the propagation of pressure surges through full bore flow carrying pipe systems. For example the pressure variations following inadvertent power failure to a pipeline pumping station often provides the system design condition and leads to the need to introduce safety systems such as air chambers, increased pump inertia or by pass systems. Similarly the surges generated by load rejection by hydro-electric power station turbines lead to surge propagation in the water supply tunnels, normally dealt with by the inclusion of surge shafts cut into the rock surrounding the hydroplant supply tunnels.

The vast majority of research into unsteady flow has therefore been directed towards the large civil engineering applications such as power stations, cross country oil, water or sewage pipelines. Currently these areas are well documented and several texts are available describing appropriate analysis and design techniques [1,2].

The prediction techniques currently employed may be traced back to the late 19th century and for many years were based on the Bergeron graphical methods, that incidentally also find application in electrical surge problems.

The widespread availability of digital computers from the 1960's introduced or made practical, more versatile methods. Although translations of the graphical techniques were used initially, the numerical method of characteristics employed to solve the differential equations defining the unsteady flow has now come to be widely accepted as the more versatile technique [3].

As mentioned the applications to be found in the literature refer almost exclusively to large scale civil engineering applications. However, the problem of unsteady flow translates across the boundaries of scale, being dependent on the relationship between the rate of change of boundary conditions and the propagation rate of transient pressures within the system. Such applications may be found in a wide range of small scale systems, including, for example, diesel fuel injection systems. The analysis technique based on the method of characteristics solution was successfully applied to a transient analysis of the Concorde fuel system, both in the ground refuelling mode and the in flight fuel transfer and emergency ejection modes [4]. Similarly the methodology has been applied to airport hydrant refuelling networks.

Although this vast bank of experience and literature exists it is, as mentioned, primarily directed to full bore flow large civil engineering applications.

Unsteady flow may, by definition, also occur in partially filled pipe or open channel flow. Again the available literature applies to the large excavated straight sided channels to be found in such applications as power station turbine discharge channels. In the open channel flow situation the full bore flow transient pressure changes are replaced by channel depth variations, pressure waves moving at the appropriate sonic velocity being replaced by surface waves. The simplification possible in air or vapor free fluid full bore flow that the wave propagation speed is constant, depending only on the liquid and pipe materials and dimensions, no longer holds as the wave propagation speed depends on flow depth and channel shape. Thus an extra variable is effectively added to the local flow velocity and pressure, or depth, namely the local wave speed.

As will be seen in the analysis presented this also introduces other difficulties in the numerical solution of the governing equations since the uniform x-t grid system generally employed has to be modified to allow for variable characteristic slope as the local wave speed varies.

As with the scale translation from hydroelectric plant to aircraft fuel system, so too does the basic flow analysis translate from large excavated open channels to partially filled drain piping systems. The boundary conditions change to represent, for example, varying inflow dependent on the appliances connected to the system. The channel cross sectional shape does not constrain the application of the fundamental analytical approach.

At present no numerical analysis technique has been documented to predict the depth and flow rate along gravity driven unsteady flow in partially filled drainage sized systems; however the analysis techniques incorporating the method of characteristics together with boundary conditions expressed in terms of time dependent depth or flow rates may be employed.

The current report is designed to act as an introduction to the use of these methods to predict depth-time profiles along a simulated drain. In particular the analysis will attempt to predict the depth history upstream of a deposited solid in the drain pipe as a prelude to a consideration of the forces acting on the solid and its subsequent motion along the drain pipe.

In addition the analysis techniques are shown to be applicable to determine flow attenuation in long drain pipes, this topic being considered increasingly important due to the probable reduction in overall system flow rates due to water conservation proposals.

Similarly the techniques can be applied to pipe sizing calculations in order to avoid the occurrence of local full bore flow and associated venting problems.

The differential equations defining unsteady flow are presented in this report, together with the application of the method of characteristics to yield a total differential equation which may be solved by numerical methods. The method of specific time intervals is presented together with the necessary formulation of boundary equations to represent variable inflow, pipe discharge and leakage flow past the solid. Finally a computer program designed to analyze the transient depth response to a stationary solid in a pipe supplied with a variable inflow is presented together with typical output for flow and system variables representative of drainage design values.

Extension of the methods described to flow attenuation and solid motion prediction are also proposed.

2. UNSTEADY FLOW IN OPEN CHANNELS

2.1 DEFINING EQUATIONS

The equations defining one dimensional unsteady flow are presented for open channels. Frictional losses are assumed to be adequately represented by the Manning equation utilizing the local velocity and flow depth. Channel slopes are assumed small enough for cosine slope ($\cos\alpha$) to be approximately 1.

Figure 1 illustrates an elemental fluid strip. Application of the unsteady momentum equation yields:

(i)	Net hydrostatic force:	$\rho g \frac{\partial h}{\partial x} \Delta x\, A$
(ii)	Shear force on wetted: perimeter P	$-\tau_o\, P\, \Delta x$
(iii)	Gravity force in flow: direction	$\rho g\, A\, \Delta x \sin\alpha$
(iv)	Net efflux momentum:	$\frac{\partial}{\partial x}(\rho V^2 A)\, \Delta x$
(v)	Increase of momentum within:	$\frac{\partial}{\partial t}(\rho A V)\, \Delta x$

Thus the momentum equation becomes

$$-\rho g \Delta x A \frac{\partial h}{\partial x} - \tau_o P \Delta x + \rho g A \Delta x \sin\alpha = \frac{\partial}{\partial x}(\rho V^2 A)\,\Delta x + \frac{\partial}{\partial t}(\rho A V)\Delta x \qquad (1)$$

Expanding and dividing by $\rho A \Delta x$

$$g \frac{\partial h}{\partial x} + \frac{\tau_o}{\rho m} - g \sin\alpha + 2V \frac{\partial V}{\partial x} + \frac{V^2}{A} \frac{\partial A}{\partial x} + \frac{V}{A} \frac{\partial A}{\partial t} + \frac{\partial V}{\partial t} = 0 \tag{2}$$

where $m = A/P$

The continuity equation applied to the control volume of Figure 1 yields

$$\frac{-\partial (\rho A V)}{\partial x} \Delta x = \frac{\partial (\rho A \Delta x)}{\partial t} \tag{3}$$

Expanding and dividing by $\rho \Delta x$

$$V \frac{\partial A}{\partial x} + \frac{\partial A}{\partial t} + A \frac{\partial V}{\partial x} = 0 \tag{4}$$

Multiplying (4) by V/A and subtracting from equation (2) yields

$$g \frac{\partial h}{\partial x} + \frac{\tau_o}{\rho m} - g \sin\alpha + \frac{V \partial V}{\partial x} + \frac{\partial V}{\partial t} = 0 \tag{5}$$

Let $S_o = \sin \alpha$ and $gS = \tau_o/\rho m$

where S is the slope of the energy grade line as defined by the Manning equation

$$S = \frac{n^2 V^2}{m^{4/3}} \tag{6}$$

Note that $S = S_o$ only under steady uniform flow conditions.

Equation 5 becomes

$$g \frac{\partial h}{\partial x} + g(S - S_o) + \frac{V \partial V}{\partial x} + \frac{\partial V}{\partial t} = 0 \tag{7}$$

From Figure 1 $\partial A = \partial h . T.$

where T is surface width.

Hence $$\frac{\partial A}{\partial x} = T \frac{\partial h}{\partial x},$$

and $$\frac{\partial A}{\partial t} = T \frac{\partial h}{\partial t}$$

so that equation 4 becomes

$$VT \frac{\partial h}{\partial x} + T \frac{\partial h}{\partial t} + A \frac{\partial V}{\partial x} = 0 \tag{8}$$

Thus equations 7 and 8 represent the unsteady flow conditions in terms of local depth and average velocity. These equations may be solved by means of the method of characteristics.

2.2 SOLUTION BY METHOD OF CHARACTERISTICS

Equation 7 and 8 may be combined as

$$L_1 + \lambda L_2 = 0$$

where L_1 is equation 7 and L_2 equation 8

$$\left[\frac{\partial V}{\partial x} (V + \lambda A) + \frac{\partial V}{\partial t}\right]_1 + \lambda T \left[\frac{\partial h}{\partial x} (V + \frac{g}{\lambda T}) + \frac{\partial h}{\partial t}\right]_2 + g(S - S_o) = 0 \tag{9}$$

In order to solve equations 7 and 8 it is necessary to transform the equations into a total derivative expression.

For the terms in bracket [1] to become the total derivative dV/dt, it is necessary for

$$V + \lambda A = \frac{dx}{dt}$$

and for the terms in bracket [2] to become the total derivative dh/dt then

$$\frac{dx}{dt} = V + g/\lambda T$$

hence $V + \lambda A_{-} = V + g/\lambda T$

therefore $\lambda = \pm \sqrt{\frac{g}{AT}}$

and $\frac{dx}{dt} = V \pm \sqrt{\frac{gA}{T}}$

The term $\sqrt{\frac{gA}{T}}$ has dimensions of velocity and is identified as the local wave speed

$$c = \sqrt{\frac{gA}{T}} \tag{10}$$

Equation 9 may now be expressed as:

$$\frac{dV}{dt} \pm \frac{g}{c}\frac{dh}{dt} + g(S - S_o) = 0 \tag{11}$$

subject to $\frac{dx}{dt} = V \pm c$ (12)

Referring to Figure 2, if the variables V and h are known at R and S then four equations may be written in terms of the unknowns at point P, namely

$$C^+ \left[\begin{array}{ll} V_p - V_R + g \int_{h_R}^{h_P} \frac{1}{c}\, dh + \int_{t_R}^{t_P} g(S-S_o)dt = 0 & (13) \\ x_P - x_R = \int_{t_R}^{t_P} (V+c)dt & (14) \end{array} \right.$$

$$C^- \left[\begin{array}{ll} V_P - V_S + g \int_{h_S}^{h_P} \frac{1}{c}\, dh + \int_{t_S}^{t_P} g(S-S_o)dt = 0 & (15) \\ x_P - x_S = \int_{t_S}^{t_P} (V-c)dt & (16) \end{array} \right.$$

It is stressed that these equations are paired, i.e. equation 13 only holds if equation 14 is satisfied and 15 only applied if 16 is satisfied. Generally these are referred to as C^+ and C^- characteristics as shown above.

In most cases a first order integration is satisfactory, however attention must be paid to the choice of time step to ensure a stable solution, as mentioned by Fox [1].

In terms of Figure 2 the time step must be sufficiently small to ensure that points R and S fall within $\pm\ \Delta x$ on either side of point P.

Generally a suitable rule is to set

$$\Delta t = \Delta x/2c \tag{17}$$

where c is the wave speed appropriate to the initial flow in the channel prior to the initiation of unsteady flow. As will be seen the solution requires an initial steady flow in the channel, although this may be infinitesimal.

Applying a first order approximation to equations 13 to 16, in terms of Figure 2 yields

$$V_P - V_R + \frac{g}{c_R}(h_P - h_R) + g(S_R - S_o)\Delta t = 0 \tag{18}$$

$$x_P - x_R = (V_R + c_R)\ \Delta t \tag{19}$$

$$V_P - V_s - \frac{g}{c_s}(h_P - h_S) + g(S_R - S_o)\Delta t = 0 \tag{20}$$

$$x_P - x_S = (V_S - c_S)\ \Delta t \tag{21}$$

It will be noted that conditions at R and S at time $(t-\Delta t)$ are determined by interpolation between points A and C and C and B respectively. This interpolation introduces a dispersive element to the calculation as effects arriving at A, C and B at time $t - \Delta t$ are assumed, via the interpolation, to effect conditions at R and S at time $t - \Delta t$. This is comparable to increasing the local wave speed.

Interpolation effects should be minimized by arranging for R and S to fall as close as possible to A and B by adjusting the time step Δt.

Two flow regimes may be identified for open channels defined in terms of the Froude Number $Fr = V/\sqrt{gh}$

1) Subcritical flow, Froude N° < 1

Here the local wave speed is greater than the flow average velocity. Thus waves may be propagated upstream.

2) Supercritical flow, Froude N° > 1

Here the local wave speed is less than the average flow velocity at that section, hence waves may not be propagated upstream. Flow may be transformed from supercritical to subcritical via a hydraulic jump.

Figure 3 illustrates the importance of these two flow regimes on the solution of equations 13 to 16.

If $c > V$ then the conditions at P are determined by the intersection of the C^+ and C^- drawn from P into the AC and BC sections.

If $c < V$ then conditions in the downstream section BC cannot effect point P. The slope of the C^- characteristic, PS, becomes positive and both R and S lie in the AC section as shown.

For the <u>subcritical</u> flow encountered in the drainage applications considered and the equations derived below refer to this flow regime. Similar derivations may be undertaken for supercritical flow.

Referring to Figure 2 for subcritical flow:

$$\frac{V_C - V_R}{V_C - V_A} = \frac{x_C - x_R}{x_C - x_A} = (V_R + c_R)\,\frac{\Delta t}{\Delta x}$$

$$\frac{c_C - c_R}{c_C - c_A} = \frac{x_C - x_R}{x_C - x_A} = (V_R + c_R)\,\frac{\Delta t}{\Delta x}$$

and

$$\frac{h_C - h_R}{h_C - h_A} = (V_R + c_R)\,\frac{\Delta t}{\Delta x}$$

as $x_P = x_C$ and $x_P - x_R = (V_R + c_R)\Delta t$

Solution yields

$$V_R = \frac{V_C + \theta\,(-V_C c_A + c_C\,V_A)}{1 + \theta\,(V_C - V_A + c_C - c_A)} \tag{22}$$

$$c_R = \frac{c_C(1 - V_R\,\theta\,) + c_A V_R\,\theta}{1 + c_C\theta - c_A\theta} \tag{23}$$

$$h_R = h_C - (h_C - h_A)(\theta(V_R + c_R)) \tag{24}$$

Similarly

$$V_S = \frac{V_C - \theta(V_C c_B - c_C V_B)}{1 - \theta(V_C - V_B - c_C + c_B)} \tag{25}$$

$$c_S = \frac{c_C + V_s\theta(c_C - c_B)}{1 + \theta\,(c_C - c_B)} \tag{26}$$

$$h_S = h_C + \theta(V_S - c_S)(h_C - h_B) \tag{27}$$

The determination of conditions at P at time $t + \Delta t$ requires the following steps:

(i) All conditions known at time t for nodal points A B C etc.

(ii) Values of V, h and c at interpolation points R and S calculated from equations 21 - 27.

(iii) Using these values of V, h, and c the conditions at P, i.e. velocity V and depth h, at time $t + \Delta t$ are calculated by means of equations 18 and 20.

(iv) The value of wave speed c at P at time $t + \Delta t$ is calculated from equation 10. The value of flow surface width and cross sectional area are calculated from flow depth, h, and the channel shape relationships.

(v) The sequence is repeated at each time step.

2.3 APPLICATION OF SOLUTION TO DRAINAGE FLOW

Equations 18 to 21 may be expressed as:

$$\left.\begin{aligned} V_P &= X2 - X1\ h_P \\ x_P - x_R &= (V_R + c_R)\Delta t \end{aligned}\right\} \quad C^+ \qquad (28)$$

$$\left.\begin{aligned} V_P &= X4 + X3\ h_P \\ x_P - x_S &= (V_S - c_S)\Delta t \end{aligned}\right\} \quad C^- \qquad (29)$$

where $X1 = g/c_R$

$X3 = g/c_S$

$$X2 = V_R + \frac{g\ h_R}{c_R} - g(S_R - S_o)\Delta t$$

$$X4 = V_S - \frac{g\ h_S}{c_S} - g(S_S - S_o)\Delta t$$

Figure 4 illustrates a typical drainage pipe length to be analyzed in terms of flow depth and velocity at each section.

The application may be dealt with in two distinct sections:

(i) Internal or nodal points.

The values of h, V and c at all points Δx apart between $x = \Delta x$ and $x = (L - \Delta x)$ may be calculated by the sequence set out above, namely by simultaneous solution of equations 28, 29 and use of equation 10 to yield wave speed.

(ii) Boundary conditions.

In order to predict h, V and c at the system boundary it is necessary to solve either 28 or 29 with an appropriate boundary condition.

At pipe entry a suitable boundary condition would be the inflow profile

$$Q = f(t)$$

to be solved with the C^- characteristic:

$$Q(t) = V_1 A_1 = f(t)$$

$$V_1 = X4 + X3\ h_1$$

$$Q(t) = A_1\ (X4 + X3\ h_1)$$

where $A_1 = f(h_1)$

$$Q(t) = f(h_1)(X4 + X3\ h_1)$$

In the form

$$0 = Q(t) - f(h_1)\ \ (X4 - X3\ h_1) \tag{30}$$

this relationship may be solved by bisection method as values of Q are known at each time step. The channel cross section shape relationship is also required so that no direct solution of equation 30 is available for circular section channels.

At pipe exit in the subcritical flow regime the flow depth approaches the critical depth value, given by zero value of the expression:

$$\frac{Q^2}{g\ A^3_{crit}}\ T_{crit} = 1,$$

where A and T are functions of depth, h.

This condition may be solved with the C^+ characteristic

$$V_{N+1} = X2 - X1\ h_{N+1}$$

where N = N° of pipe length sections, each of length Δx.

The boundary condition becomes

$$[(X2 - X1\ h_{N+1})\ A_{N+1}]^2\ T_{N+1}/g\ A^3_{N+1} - 1 = 0 \tag{31}$$

Solution may again be achieved by use of the bisection method together with the use of the area to depth relationship for the channel.

2.4 APPLICATION OT WASTE SOLID BOUNDARY CONDITION

Considering a stationary solid deposited at some point along the waste pipe, the water depth and velocity upstream of the solid may be predicted if a suitable boundary equation may be written linking flow past the solid to upstream conditions.

Figure 5 illustrates the relationship between flow past a stationary solid and the specific energy upstream. These results were compiled during a Brunel University Drainage Research Group study of solid transport in drainage systems.

From the experimental work summarized by Figure 5, the flow past the solid may be expressed by the following relationship:

$$Q = K(h + \frac{V^2}{2g} - SE_o)^2 \tag{32}$$

where $SE = h + V^2/2g$, flow specific energy and SE_o is the flow specific energy required for flow initiation past the solid (when $SE_o \neq 0$)

Equation 32 may then be solved with the C^+ characteristic

$$V_{N+1} = X2 - X1\ h_{N+1}$$

where $Q = V_{N+1}\ A_{N+1}$

so that

$$A_{N+1}\ (X2 - X1\ h_{N+1}) = K\ [h_{N+1} + \frac{1}{2g}\ (X2 - X1\ h_{N+1})^2 - SE_o]^2$$

This expression results in a quartic in terms of water depth upstream of the solid, h_{N+1}, see Appendix 2.

This quartic must be solved by an iterative technique as the flow area, A_{N+1}, is a function of h_{N+1}.

The Newton-Raphson method may be employed to carry out the necessary iteration solution.

Once the value of h_{N+1} has been determined the value of V_{N+1} and c_{N+1} may be determined from equation 28 and 10.

As mentioned the SE_o term is the flow specific energy required to initiate flow past the stationary solid. If the value of flow specific energy at time t is less that SE_o then the value of flow velocity at the solid at time $t + \Delta t$ is set equal to zero. The flow depth then comes directly from equation 28 as:

$$h_{N+1} = X2/X1 \tag{33}$$

This implies that the flow depth upstream of the solid must rise to SE_o prior to the initiation of flow past the solid.

This solution is set out in detail in Appendix 2.

In this model no account is taken of flow downstream of the solid.

From Figure 5 the flow past the solid may alternatively be expressed as

$$Q = K_1 \left(SE_U - SE_D \right)^2$$

where SE_U, SE_D are the specific energy values immediately upstream and downstream of the solid.

This boundary equation may be used to link the flow conditions upstream and downstream of the solid, for example the upstream flow is governed by the C^+ equation 28 and that downstream is governed by the C^- equation 29.

This formulation of the boundary condition would allow a series of nodal points downstream of the solid to be dealt with, the pipe being then terminated by the boundary condition already described, i.e. critical depth at discharge.

The techniques described above have been included in a Fortran program TRANSCA run on the NBS Center for Building Technology Perkin Elmer 732 computer.

This program is included in Appendix 1 together with a flow chart and description and sample input data while representative program output are included in Appendix 3.

3. PROGRAM OUPUT AND DEVELOPMENT

Figures 6, 7 and 8 illustrate the predicted depth and flowrate at sections along the simulated drain pipe considered, while Appendix 3 presents typical program output.

The program calculation technique requires a known steady uniform flow to be set up along the channel prior to the calculation of unsteady conditions. In the model presented this is assumed to be established with no solid in the pipe. The calculation then assumes the presence of the solid from the first time step onwards. This explains the depth increasing wave that is shown in Figure 8 moving upstream from the solid boundary. This is merely a function of the initial conditions chosen.

An alternative base condition would be either steady flow with the solid in place, with the associated back water profile upstream of the stationary solid, or stationary fluid trapped behind the solid. In both cases the fluid depth would increase at the solid location, forming the expected backwater curve profile.

The former set of flow conditions could have been achieved in the current simulation by holding the inflow rate constant, however this would have required a longer computer run. The establishment of steady conditions is demonstrated in Figure 6 as the inflow profile is assumed to become constant.

The results demonstrate that the techniques described may be employed to yield values of depth and flowrate under unsteady flow conditions in open channel flow. In particular the results indicate that the concept and use of specific energy to leakage flow characteristic, rather akin to a valve pressure flow relationship, is capable of accurately describing the boundary conditions at a stationary solid. The values of depth at the solid with time obviously require experimental verification, however the depths predicted are generally in line with observations of water build up behind stationary solids made during the Brunel University drainage investigations.

Two main development paths may be proposed based on the analysis techniques described:

(i) Application to the moving solid case.

This case would require the introduction of flow relative velocity into the boundary conditions describing the solid described above. It is proposed that, once this has been done, the stationary solid specific energy differential across the blockage to flow past relationship is assumed to apply to the moving case.

A number of unknowns are required to obtain a solution, namely the force balance necessary to be overcome to initiate motion and the solid-flow momentum equation that would determine solid velocity and distance traversed in each time step.

One simplifying assumption that could be made would be to assume that the flow ahead of the solid, i.e. downstream, assumes the normal depth and velocity characteristic to the channel dimensions and the flow past the solid.

This case is currently being considered.

(ii) Application of the techniques described to the prediction of flow attenuation in long channels.

At first sight it would appear that the existing program would be capable of dealing with this case, however the errors due to interpolation made necessary by the adoption of a fixed time-distance grid, Figure 2, could introduce errors. The interpolation techniques effectively disperse the moving wave fronts and would tend to overestimate the attenuation produced.

A free grid in which both time and distance become calculated variables is a solution to this problem. This is not normally done as it results in a rather "untidy" output, however this method will be investigated as part of the current investigation.

As mentioned the method of characteristics requires that there be an initial steady flow condition along the channel, or that the flow is at rest at known depth. This limiting condition is necessary to provide the base values of depth, velocity and wave speed at each calculating position. The influence of magnitude of this initial assumed flow on the attenuation of a constant superimposed inflow will also be considered as part of (ii) above, together with an assessment of the effect of the interpolation ratio employed in choosing the appropriate calculation time step.

4. CONCLUSIONS

The program presented indicates that the techniques involved in the solution of unsteady flow problems via the method of characteristics may be applied to partially filled drainage pipeflow.

The methods presented will be employed to investigate further their application to solid waste transport analysis and to the study of flow attenuation in long channels, typically representative of underground building drainage systems.

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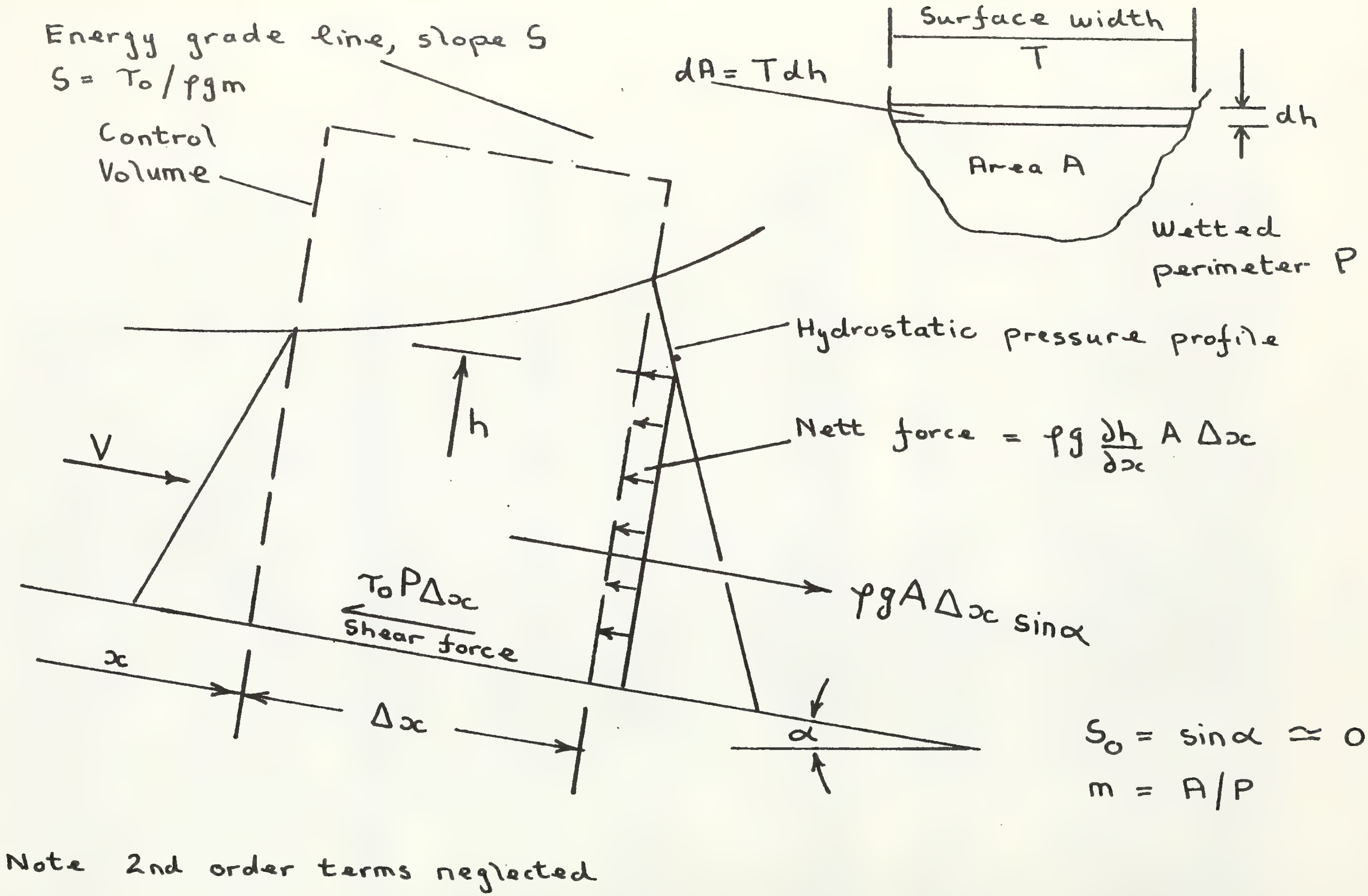


Figure 1. Application of momentum equation to unsteady flow in a general open channel.

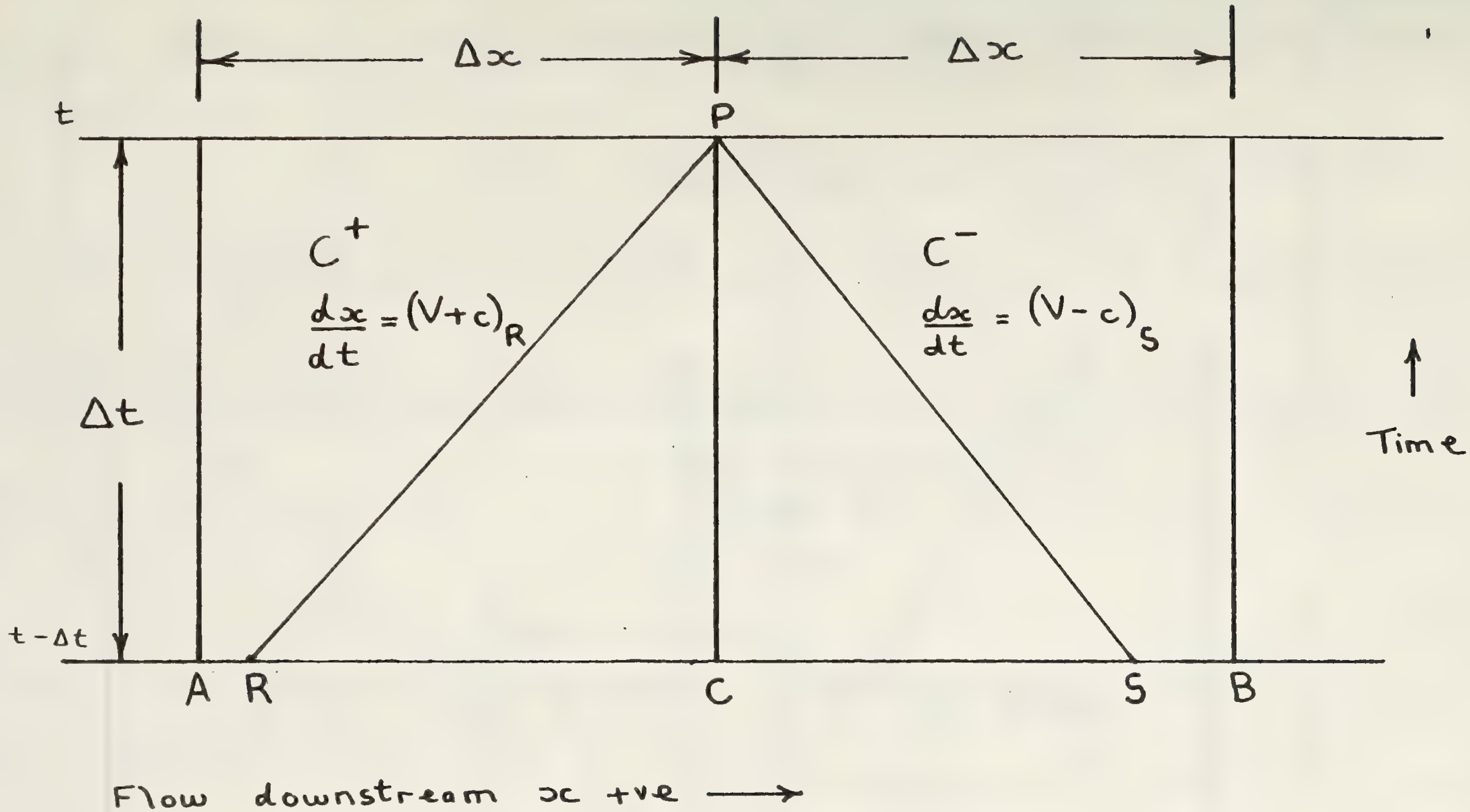
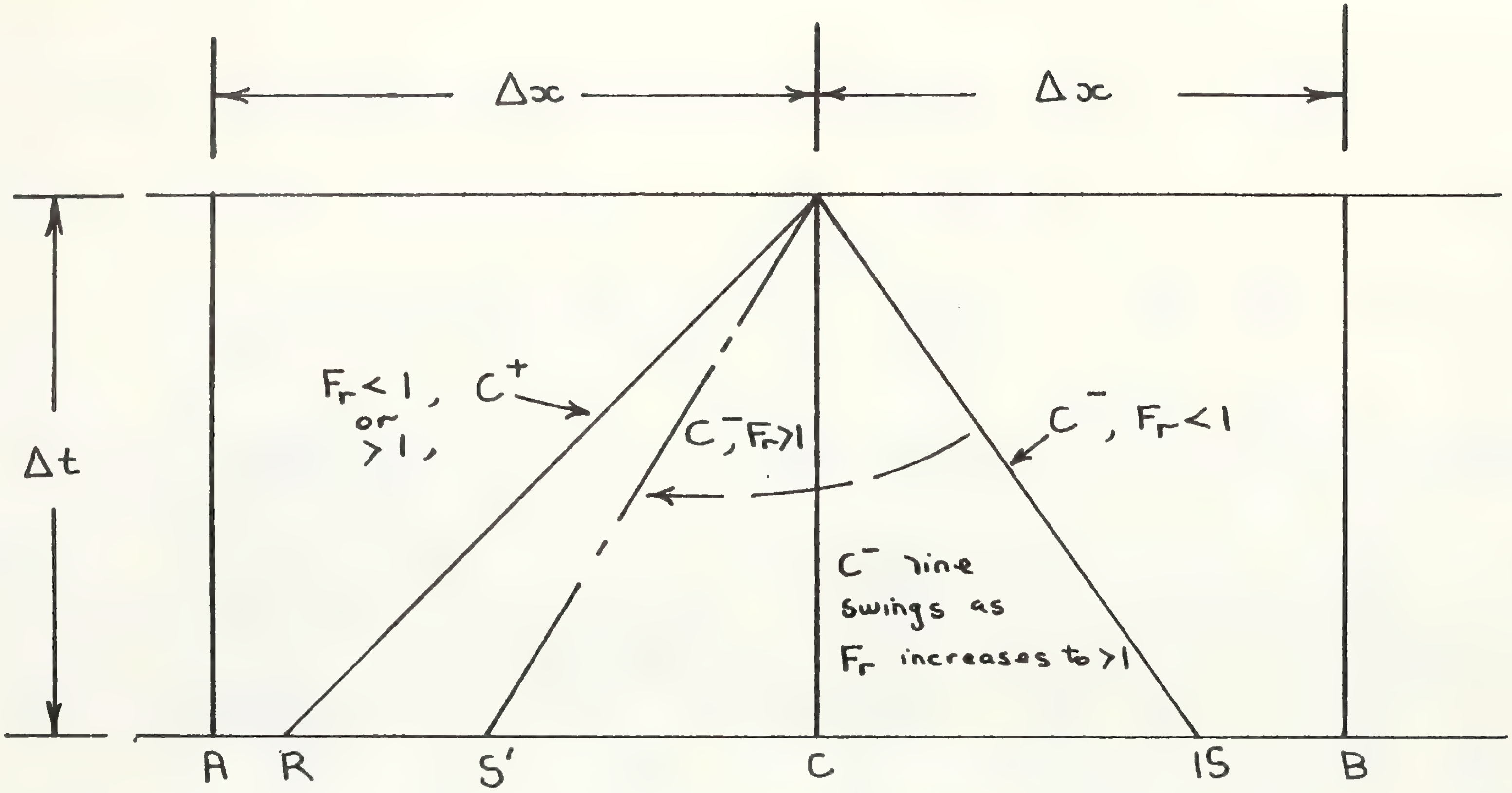


Figure 2. Specified time interval technique, illustrating necessity for base condition interpolation.



F_r = Froude N°. < 1 subcritical flow, S lies in downstream section CB

> 1 supercritical flow, S' lies in upstream section AC.

Figure 3. Modification to specified time interval grid for sub and supercritical flow regimes.

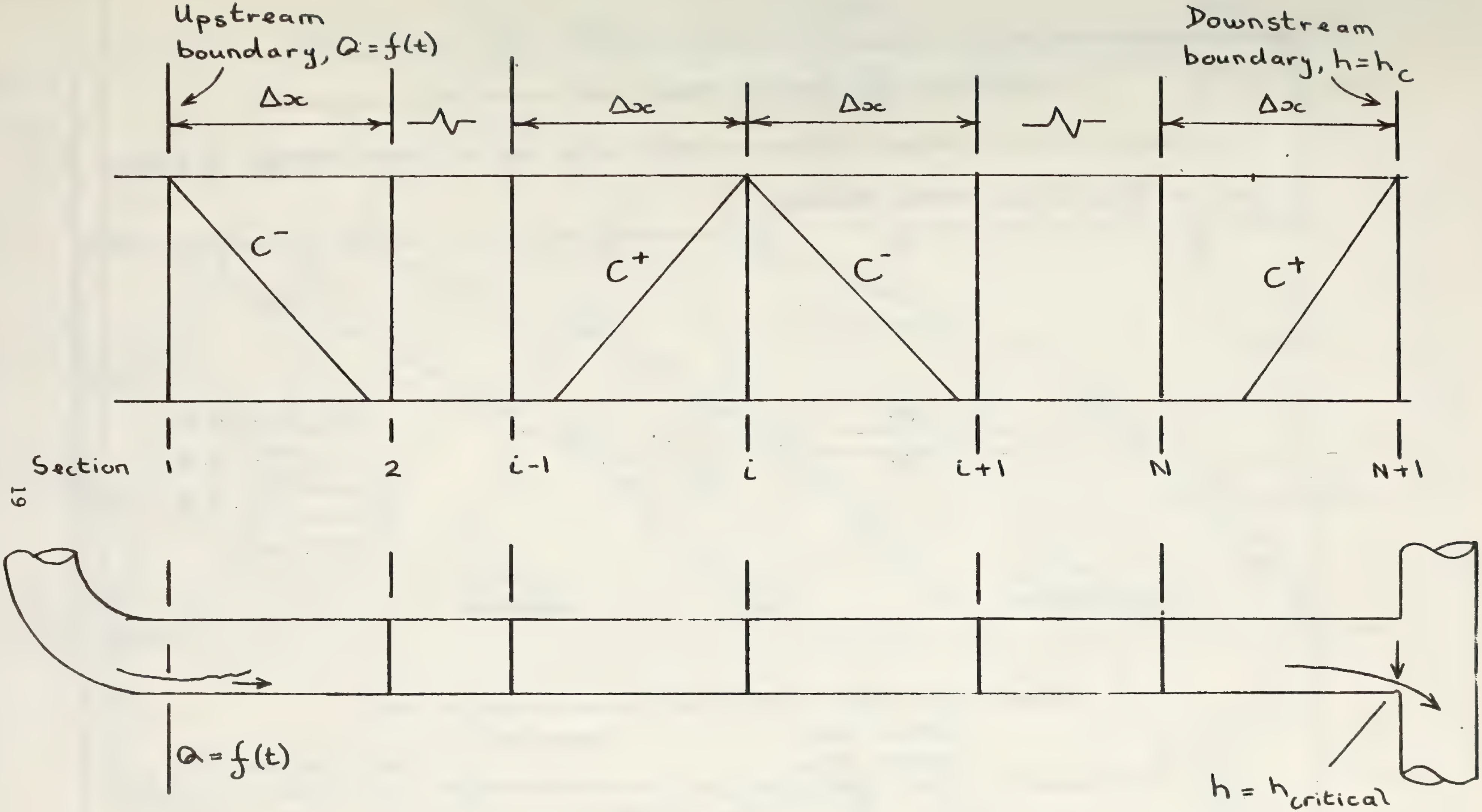


Figure 4. Application of specified time interval grid to simple channel with known entry and exit boundary equations.

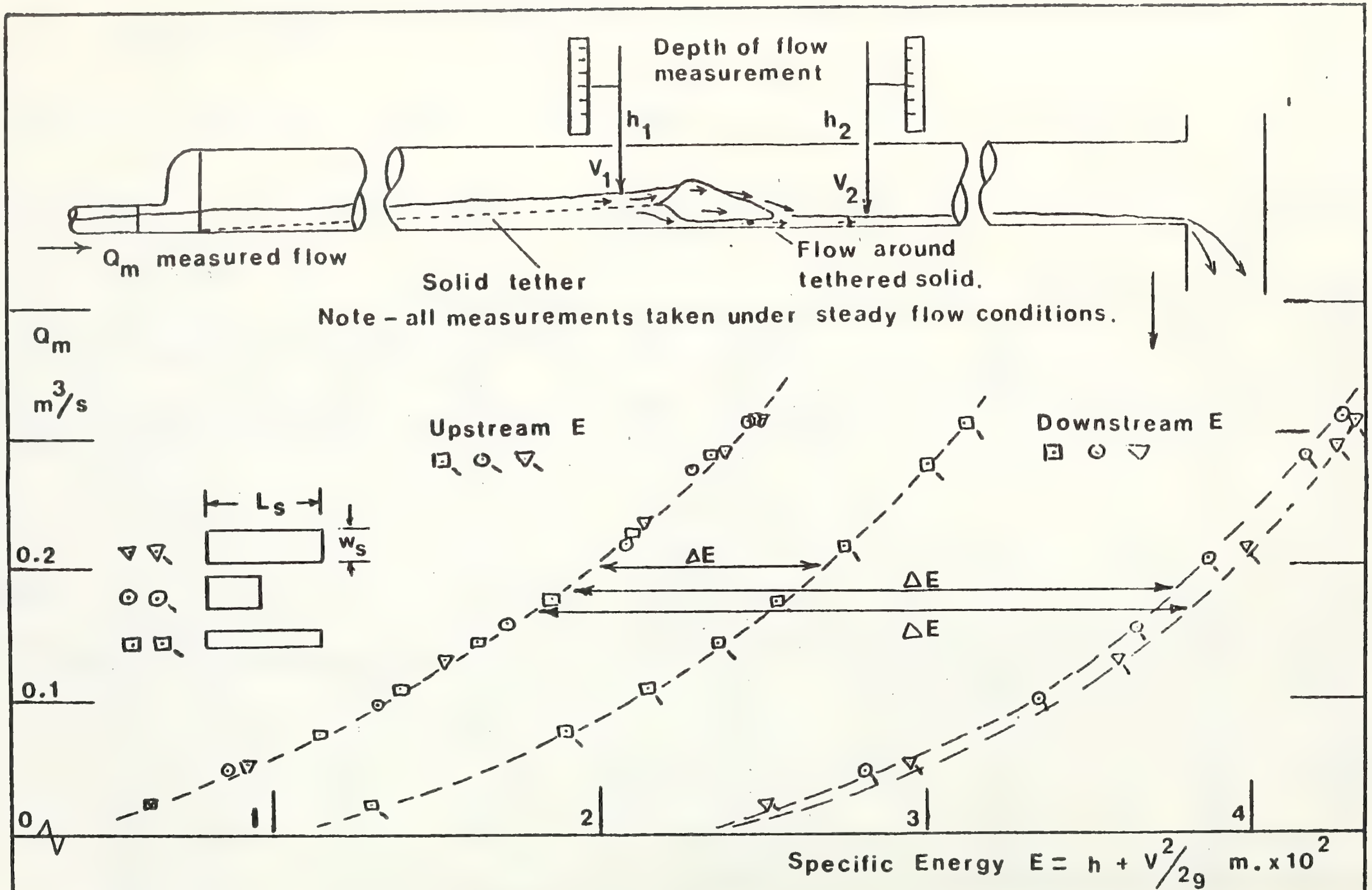


Figure 5. Measurement of the flow specific energy change across a solid tethered in the waste pipe under steady flow conditions.

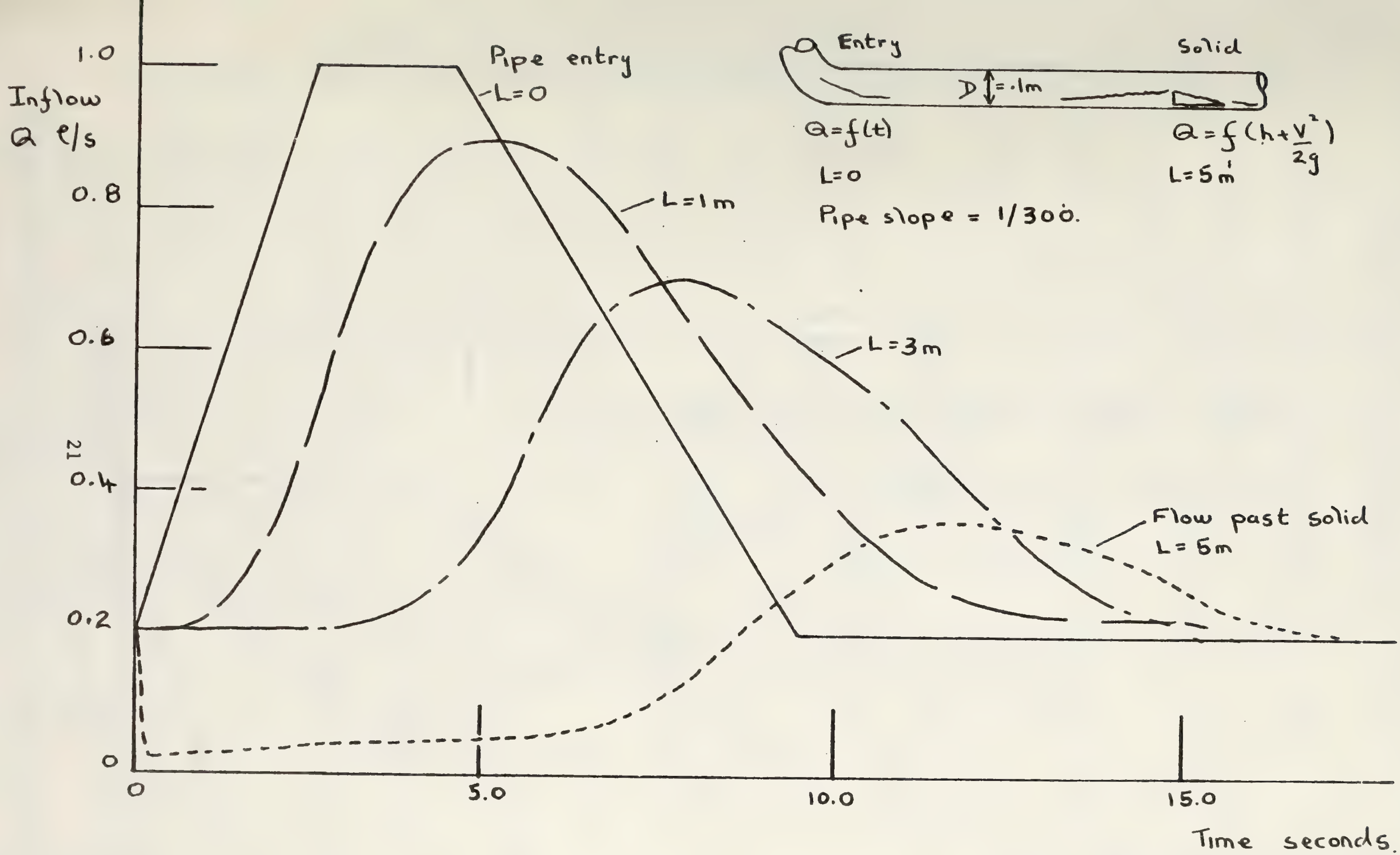


Figure 6. Flowrate vs time profiles at pipe entry, solid boundary and intermediate points along the simulated drain pipe.

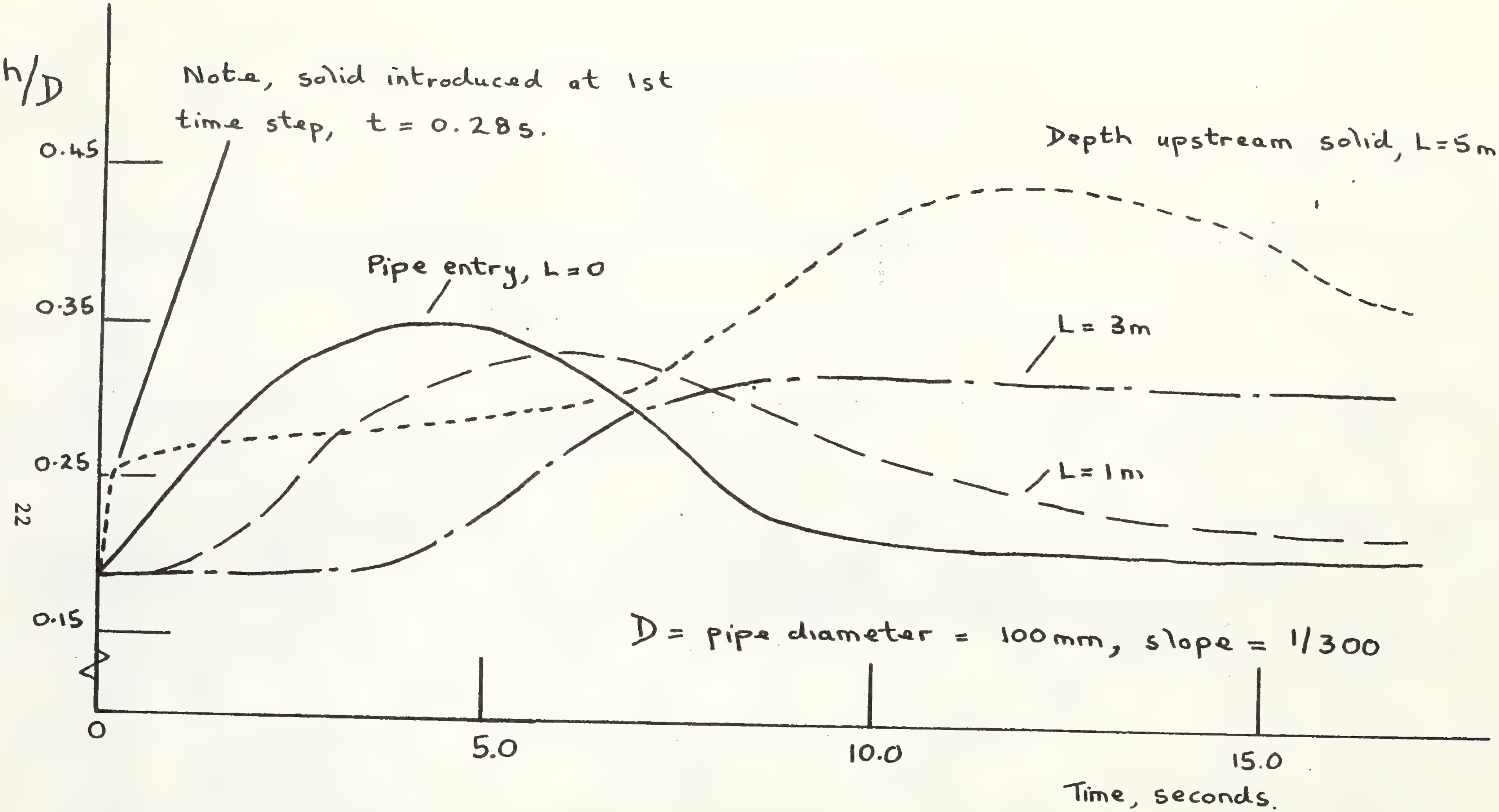


Figure 7. Depth vs time profiles along the simulated drainage pipe following an inflow variation.

Figure 8. Depth profiles along the 5m simulated drain at 14 time intervals illustrating surface wave motion.

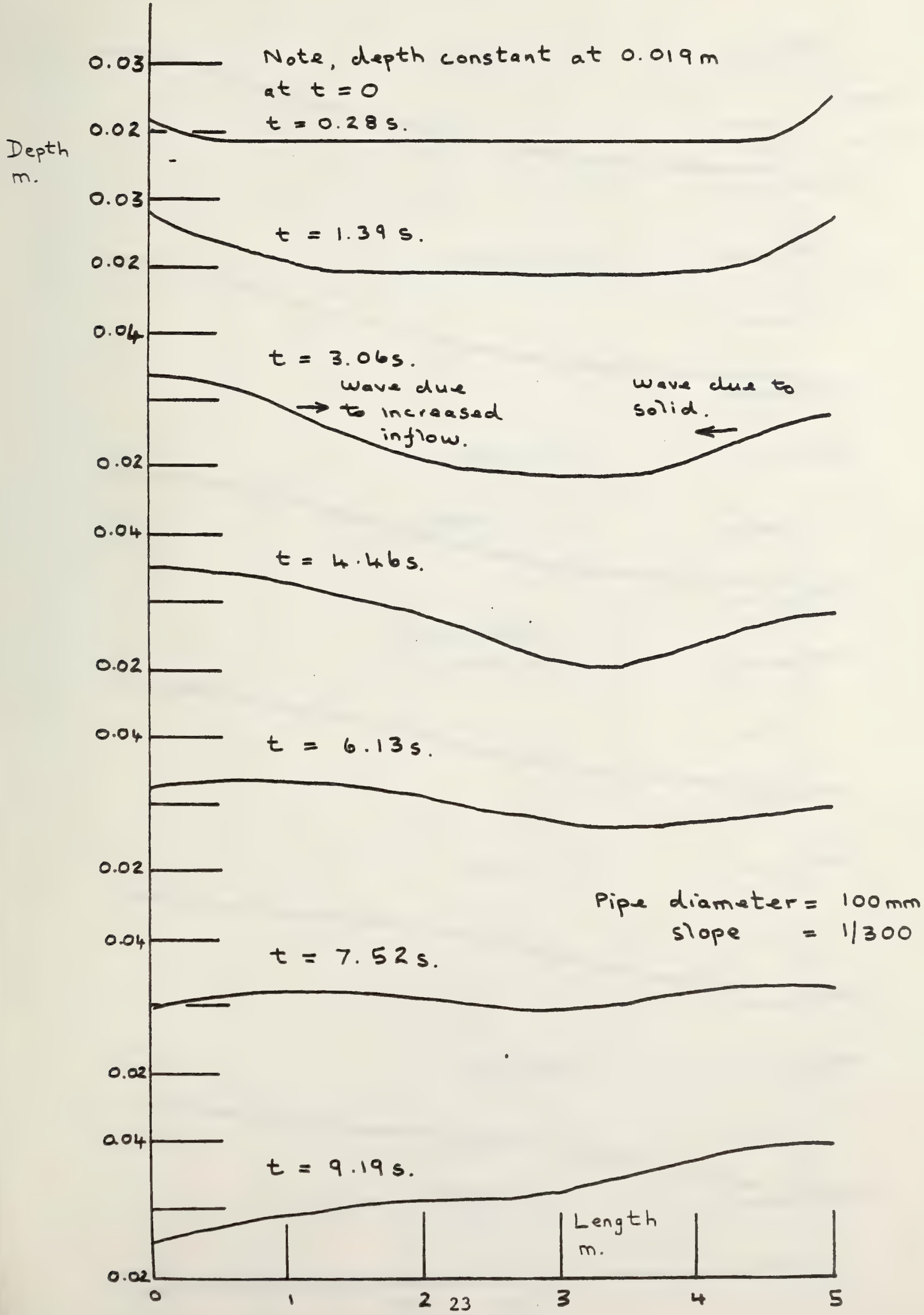
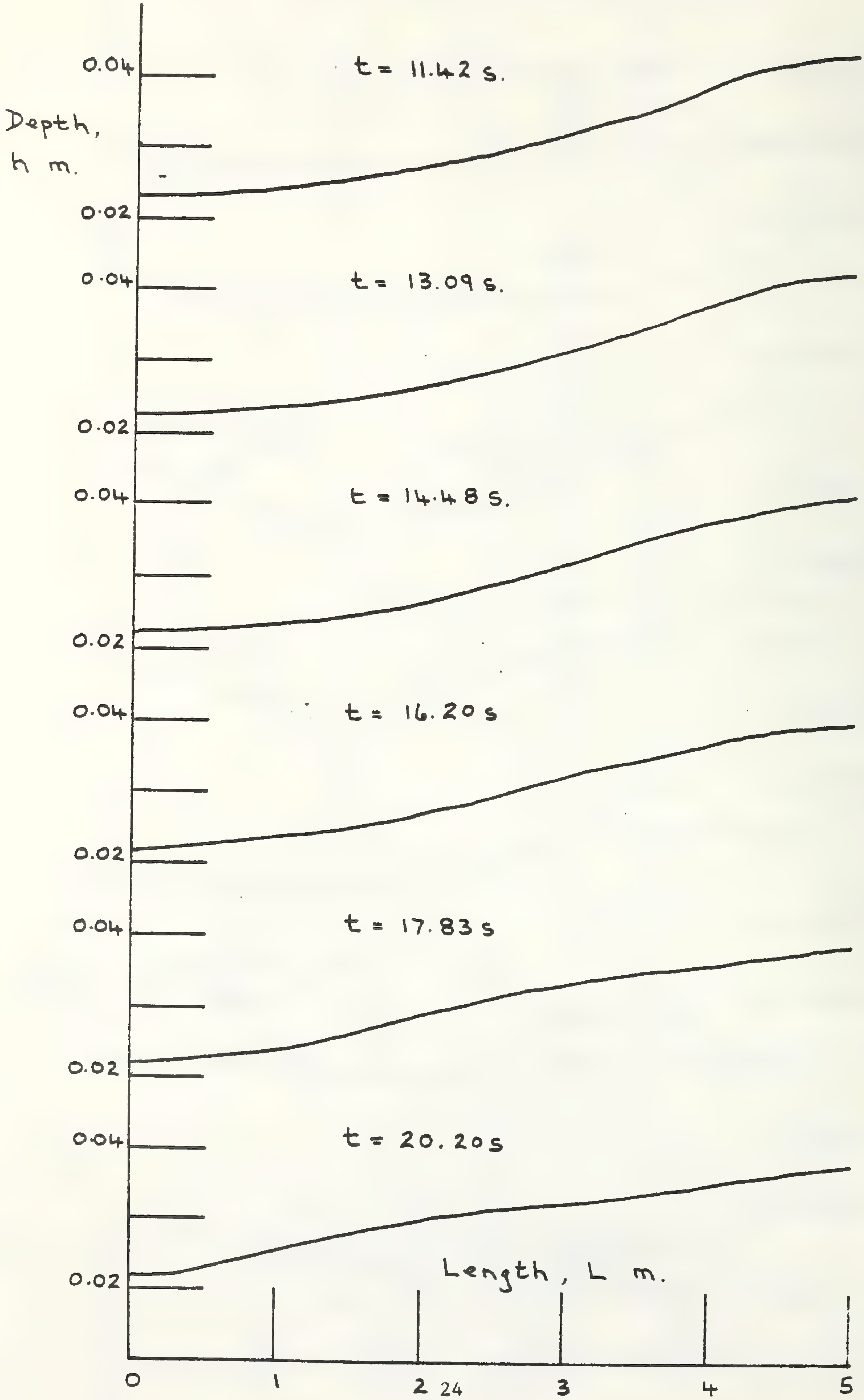


Figure 8 cont. Depth profiles along the 5m simulated drain at 14 time intervals illustrating surface wave motion.



Appendix 1

Program TRANSCA

Program TRANSCA

This appendix presents a complete print out of this program, written in Fortran, together with a flow chart and sample input data. The program was run on the NBS Center for Building Technology Perkin Elmer 732 computer.

It was found necessary to employ double precision calculating techniques in the program due to the inclusion of calculations involving the root of small differences between large numbers. Otherwise no special facilities are required.

The program accepts data in SI units with the exception of the inflow profile, this is read in as litres/second and corrected to m^3/s within the program.

FLOW CHART PROGRAM TRANSCA.

Set up initial conditions:

Time = 0.0

Read pipe data, diameter D, Manning coeff. RM,
slope SØ, length PL.

Read solid data, SEØ - min. specific energy to establish flow past solid.
XK - coeff. in $Q = XK (SE-SE\emptyset)^2$ solid characteristic.

Read calculation data, N - N° pipe sections,
TMAX - duration calculation
TFAC - time step factor

Read inflow profile, NPTS - N° of coordinate pairs assumed linked by straight line
Flow - QIN, time TIN.

Adjust flow from l/s data to m^3/s for calc.

↓

Calculation of initial steady uniform conditions at time zero

CALL DEPTH - calc. flow normal depth HN.
CALL SHAPE - calc. flow area, A, width, T.
CALL WAVESPD - calc. initial wave speed CN
Calc. steady state loss from Manning eqn.

↓

Assign time zero values along pipe.

VP = QIN/A, QP = QIN,
HP = HN, CP = CN

↓

Set up interpolated points R, S to serve as base conditions for next time step
HR = HS = HP, VR = VS = VP,
CR = CS = CP, SR = SS = SLØ.

↓

CALL ASSIGN - equate HP - H, VP - V, CP - C

↓

Calculation of time step DT
DX = PL/N, DT = DX/(TFAC * CN)

↓

WRITE Initial conditions and descriptions
Output table headings
Output HP, VP, QP, CP at each DX increment, N+1 points.

↓

A. Update time and commence unsteady flow simulation.

TIME = TIME + DT.

↓

CHECK TIME VS TMAX

TIME < TMAX, GOTO B

TIME ≥ TMAX, GOTO E

Note - unsteady flow simulation achieved via a series of subroutines as follows

CALL INFLOW - calc. of appropriate point on inflow vs. time profile, Q.

↓

CALL INTER - interpolation technique to provide HR, HS etc from H, V values.

↓

CALL LOSS - calculation of friction loss terms SR, SS from HR, HS VR, VS etc.

↓

CALL ENTRY - pipe entry boundary, solution of C^- characteristic with known inflow Q at time t.

↓

CALL NODAL - solution of C^+, C^- characteristic for each of the pipe section $i = 2$ to N.

↓

CALL SOLID - solid boundary, solution of C^+ characteristic with specific energy vs flow past characteristic for solid.

↓

CALL ASSIGN — reassign arrays H, V, and C based on HP, VP and CP values above to act as base for next time step.

↓

WRITE - values of HP, VP, QP, CP for each calculated point, i = 1, N+1.

↓

GOTO A

E. End of simulation

Note (i) Subroutine SHAPE called from most other subroutines. SHAPE calculates flow area, surface width etc based on circular pipe cross section geometry. Alternative channel shape investigations using TRANSCA only require replacement of geometry equations in SHAPE.

(ii) Double precision calculation required, mainly due to the need to √ differences of large numbers, DP. need if these differences small.

SAMPLE INPUT DATA

PROGRAM TRANSCA.

Line 1

Pipe diameter, Manning coeff., slope, length.

Format 4F10.4

▽▽▽▽0.1000 ▽▽▽▽0.0150 ▽▽▽▽0.0033 ▽▽▽▽5.0000

Line 2

Solid minimum specific energy, SE vs Q coeff, XK.

Format 2F10.4

▽▽▽▽0.0200 ▽▽▽▽0.6000

Line 3

N° calculation sections, TMAX, Time step factor

Format I3, 2F10.4

▽10 ▽▽▽25.0000 ▽▽▽▽5.0000

Line 4

N° pairs of coordinates on inflow-time curve.

Format I3

▽▽5

Lines 5 – 9

Inflow QIN at time TIN

Format 2F10.4

▽▽▽▽0.2000 ▽▽▽▽0.0000

▽▽▽▽1.0000 ▽▽▽▽2.5000

▽▽▽▽1.0000 ▽▽▽▽4.5000

▽▽▽▽0.2000 ▽▽▽▽9.5000

▽▽▽▽0.2000 ▽▽▽25.0000

Input data - units:-

S.I. units used in program TRANSC except specific energy in m.

S.I. units used in data input fields except for inflow profile data. QIN is read in l/s and converted to m^3/s in the program. QP output is l/s, otherwise SI used in output fields

Note value of XK, coefficient in solid boundary equation $Q = XK\,(SE - SE\emptyset)^2$ is read in m^2/s.

TRANSCA

AC=00032

08:11:15

08/20/80

```
C$$CDR
C       TRANSCA IS A PROGRAM DESIGNED TO APPLY THE METHOD OF
C       CHARACTERISTICS SOLUTION TO THE EQUATIONS DEFINING
C       UNSTEADY FLOW IN PARTIALLY FILLED CHANNELS.
C
C
        DOUBLE PRECISION QP(30),QIN(30),TIN(30),VP(15),HP(15),CP(15)
        DOUBLE PRECISION V(15),H(15)
        DOUBLE PRECISION VR(15),HR(15),CR(15),VS(15),HS(15),CS(15),SS(15)
        DOUBLE PRECISION SR(15),XR(15),XS(15),XN(15),C(15)
        DOUBLE PRECISION TIME, D,RM,SO,PL,SEO,XK,TMAX,TFAC
        DOUBLE PRECISION HN,HC,A,T,PER,CN,SLO,Q
        DOUBLE PRECISION DX,DT,DTO,DTRAT
        COMMON/CM1/DTO,DT,DX,D,SO,PL,SEO,XK,RM
        COMMON/CM2/N,TMAX
        COMMON/CM3/NPTS,QIN,TIN
        COMMON/CM4/V,H,C,VR,HR,CR,XR,SR,VS,HS,CS,XS,SS,XN
        COMMON/CM5/HC,HN
        COMMON/CM6/QP,VP,HP,CP
C
C
C
C
C
C
C
C
C       SET INITIAL CONDITIONS
        TIME=0.0
C       READ PIPE DESCRIPTION DATA
        READ(4,100)D,RM,SO,PL
C       D-DIA. RM-MANNING COEFF. SO-PIPE SLOPE. PL-PIPE LENGTH
100     FORMAT(4F10.4)
C       READ SOLID DESCRIPTION DATA
        READ(4,101)SEO,XK
C       SEO-SPECIFIC ENERGY REQUIRED FOR FLOW PAST SOLID.
C       XK-FLOW TO SPECIFIC ENERGY COEFF. AT SP VALUES ABOVE SEO.
101     FORMAT(2F10.4)
C       READ CALCULATION DATA
        READ(4,103)N,TMAX,TFAC
C       N-NUMBER OF PIPE SECTIONS CONSIDERED, TMAX-DURATION OF CALC.
C       TFAC-TIME STEP FACTOR,1-10.
103     FORMAT(I3,2F10.4)
C       READ INFLOW DATA PROFILE. INFLOW PROFILE USED IS BASED ON
C       A LINEAR INTERPOLATION BETWEEN THESE DATA POINTS. NOTE DATA
C       READ IN IN L/S BUT USED IN PROGRAM IN M**3/S.
        READ(4,102)NPTS
102     FORMAT(I3)
        DO 50 I=1,NPTS
        READ(4,104)QIN(I),TIN(I)
104     FORMAT(2F10.4)
        QIN(I)=QIN(I)/1000.0
50      CONTINUE
C
C
C
C
C
C       CALCULATION OF STEADY UNIFORM FLOW DEPTH BASED ON INITIAL FLOW
C       RATE QIN(1) PLUS CALCULATION OF INITIAL WAVESPEED AND LOSS
C       TERM SLO
        CALL DEPTH(TIME)
        CALL SHAPE(HN,A,T,PER)
        CALL WAVSPD(HN,CN)
```

```
      SLO=(RM**2)*((QIN(1)/A)**2)/(A/PER)**1.3333
C     ASSIGN TIME ZERO CONDITIONS ALONG TEST PIPE.
      DO 51 I=1,N+1
      VP(I)=QIN(1)/A
      QP(I)=QIN(1)*1000.0
      HP(I)=HN
      CP(I)=CN
51    CONTINUE
      XN(1)=0.0
      DO 52 I=2,N+1
      SR(I)=SLO
      VR(I)=QIN(1)/A
      HR(I)=HN
      CR(I)=CN
      XN(I)=XN(I-1)+PL/FLOAT(N)
52    CONTINUE
      DO 53 I=1,N
      SS(I)=SLO
      VS(I)=QIN(1)/A
      HS(I)=HN
      CS(I)=CN
53    CONTINUE
      CALL ASSIGN(N)
C     CALCULATION OF TIME STEP AND LENGTH SECTION.
      DX=PL/FLOAT(N)
      DT=DX/(TFAC*CN)
      DTP=DT
C
C
C
C
C
C
C
C
C     OUTPUT TEST DESCRIPTION PLUS INITIAL CONDITIONS.
      WRITE(3,202)D,RM,SO,PL
202   FORMAT(1H1,/10X,'TEST PIPE CONFIGURATION:-',
     1 /10X,'DIAMETER = ',F10.4,' M.',
     1 10X,'MANNING COEFFICIENT:-',F10.4,
     1 /10X,'PIPE SLOPE = ',F10.4,'     PIPE LENGTH = ',
     1 F10.4,' M.',//)
      IF(HC.GT.HN) WRITE(3,200)HN,HC
      IF(HC.LE.HN) WRITE(3,201)HN,HC
200   FORMAT(10X,'FLOW SUPERCRITICAL, ','NORMAL DEPTH = ',F10.4,
     1 ' M.',' AND CRITICAL DEPTH = ',F10.4,' M.',//)
201   FORMAT(10X,'FLOW SUBCRITICAL, ','NORMAL DEPTH = ',
     1 F10.4,' M. AND CRITICAL DEPTH = ',F10.4,' M.',//)
      WRITE(3,203)QIN(1),HN,CN
203   FORMAT(10X,'INITIAL FLOW RATE = ',F10.4,' M**3/S.',
     1 ' INITIAL DEPTH = ',F10.4,' M.',
     2 ' INITIAL WAVE SPEED = ',F10.4,' M/S.',/)
      N1=N+1
      WRITE(3,204)DT,DX,N1
204   FORMAT(10X,'CALCULATION TIME STEP = ',F10.4,' S.',
     1 'LENGTH INCREMENT = ',F10.4,' M.',' NUMBER OF NODES = ',I3,/)
C     OUTPUT TEST SIMULATION RESULTS.
      WRITE(3,205)(XN(I),I=1,N1)
205   FORMAT(/18X,' POSITION FROM ',11F7.4,/,18X,' ENTRY M.',/)
      WRITE(3,206)TIME,(HP(I),I=1,N1)
206   FORMAT(2X,'TIME = ',F6.3,' S.',' DEPTH',7X,'M=',11F7.4)
      WRITE(3,207)(VP(I),I=1,N1)
      WRITE(3,307)(QP(I),I=1,N1)
307   FORMAT(18X,' FLOW RATE L/S=',11F7.4)
      WRITE(3,208)(CP(I),I=1,N1)
207   FORMAT(18X,' VELOCITY  M/S=',11F7.4)
```

```
205     FORMAT(13X,' WAVE SPD. M/S=',11F7.4,/)
C
C
C
C
C
C       UPDATE TIME AND CHECK CALCULATION LENGTH.
600     CONTINUE
501     TIME=TIME+DT
        IF(TIME.GT.TMAX) GOTO 500
C
C
C
C
C
C
C       SET UP CALCULATIONS FOR THIS TIME STEP.
        DTRAT=DT/DTO
        IF(DTRAT.LT.0.06) GOTO 500
        CALL INFLOW(TIME,J)
        J1=1
        CALL INTER(N)
        J1=2
        CALL LOSS(VR,VS,HR,HS,N,SR,SS,RM)
        J1=3
        CALL ENTRY(TIME)
        J1=4
        CALL NODAL(N)
        J1=5
        CALL SOLID(TIME)
        IF(DT.LT.DTO) GOTO 600
        DT=DTO
        J1=6
        CALL ASSIGN(N)
        J1=7
        WRITE(3,206)TIME,(HR(I),I=1,N1)
        WRITE(3,207)(VR(I),I=1,N1)
        WRITE(3,307)(GR(I),I=1,N1)
        WRITE(3,208)(CR(I),I=1,N1)
        GOTO 501
500     CONTINUE
        END
C
C
C
C
C
C
        SUBROUTINE LOSS(VR,VS,HR,HS,N,SR,SS,RM)
        DOUBLE PRECISION VR(15),VS(15),HR(15),HS(15),SR(15),SS(15)
C       THIS SUBROUTINE CALCULATES THE EQUIVALENT STEADY STATE
C       LOSS BASED ON THE MANNING COEFFICIENT.
        DOUBLE PRECISION A,T,PER,RM
        DO 1 I=2,N+1
        CALL SHAPE(HR(I),A,T,PER)
        SR(I)=((VR(I)**2)*RM**2)/(A/PER)**1.333
1       CONTINUE
        DO 2 I=1,N
        CALL SHAPE(HS(I),A,T,PER)
        SS(I)=((VS(I)**2)*RM**2)/(A/PER)**1.333
2       CONTINUE
        RETURN
        END
C
C
C
```

```
C
C
C
C
C
      SUBROUTINE DEPTH(TIME)
C     THIS SUBROUTINE USES A SECTION OF ENTRY TO CALCULATE NORMAL
C     AND CRITICAL FLOW DEPTHS.
      DOUBLE PRECISION QIN(30),TIN(30)
      DOUBLE PRECISION HC,HN,TIME
      COMMON/CM3/NPTS,QIN,TIN
      COMMON/CM5/HC,HN
      CALL ENTRY(TIME)
      RETURN
      END
C
C
C
C
C
C
C
C
      SUBROUTINE INFLOW(TIME,QAV)
C     THIS SUBROUTINE CALCULATES INFLOW RATES AT PIPE ENTRY BASED
C     ON THE ENTRY FLOW PROFILE DATA. NOTE THAT THE Q CALCULATED
C     IS AN AVERAGE VALUE FOR THIS TIME STEP.
      DOUBLE PRECISION Q(30),T(30),QX(30)
      DOUBLE PRECISION QAV,DTO,DT,DX,SO,PL,SEO,XK,XM
      DOUBLE PRECISION T1,TO,TX
      COMMON/CM1/DTO,DT,DX,D,SO,PL,SEO,XK,XM
      COMMON/CM3/NPTS,Q,T
      T1=TIME
      TO=TIME-DT
      J=1
      TX=T1
      DO 3 I=1,NPTS-1
      IF(TX.GE.T(I).AND.TX.LT.T(I+1)) GOTO 4
    3 CONTINUE
    4 QX(J)=Q(I)+(Q(I+1)-Q(I))*(TX-T(I))/(T(I+1)-T(I))
      QAV=QX(1)
      RETURN
      END
C
C
C
C
C
C
C
C
      SUBROUTINE SHAPE(H,A,T,PER)
      DOUBLE PRECISION DTO,DT,DX,D,SO,PL,SEO,XK,XM,R,PI
      DOUBLE PRECISION H,A,T,PER,THETA
      COMMON/CM1/DTO,DT,DX,D,SO,PL,SEO,XK,XM
C     THIS SUBROUTINE CALCULATES FLOW AREA,SURFACE WIDTH AND
C     WETTED PERIMETER BASED ON FLOW DEPTH
      R=D/2.0
      PI=3.142
      IF(H.LT.R)THETA=2.0*DATAN(DSQRT(H*(D-H))/(R-H))
      IF(H.EQ.R)THETA=PI
      IF(H.GT.R)THETA=PI+2.0*DATAN((H-R)/(DSQRT(H*(D-H))))
      A=((D**2)/8.0)*(THETA-DSIN(THETA))
      PER=D*THETA/2.0
      T=2.0*((H*(D-H))**0.5)
      RETURN
      END
C
```

```
C
C
C
C
C
C
      SUBROUTINE WAVSPD(H,C)
      DOUBLE PRECISION H,C,AREA,T,PER
C     THIS SUBROUTINE CALCULATES WAVE SPEED BASED ON DEPTH AND CROSS
C     SECTION SHAPE.
      CALL SHAPE(H,AREA,T,PER)
      C=DSQRT(9.81*AREA/T)
      RETURN
      END
C
C
C
C
C
C
C
C
      SUBROUTINE INTER(N)
      DOUBLE PRECISION V(15),H(15),C(15),VR(15),HR(15),CR(15),VS(15)
      DOUBLE PRECISION HS(15),CS(15),SR(15),SS(15),XN(15)
      DOUBLE PRECISION XS(15),XR(15)
      DOUBLE PRECISION DT2,DT,DX,D,SO,PL,SEO,XK,RM
      DOUBLE PRECISION THETA
      COMMON/CM1/DTO,DT,DX,D,SO,PL,SEO,XK,RM
      COMMON/CM4/V,H,C,VR,HR,CR,XR,SR,VS,HS,CS,XS,SS,XN
C     THIS SUBROUTINE SETS UP, BY INTERPOLATION, THE BASE CONDITIONS
C     FOR THE NEXT TIME STEP.
      THETA=DT/DX
      N1=N+1
      DO 1 I=2,N1
      VR(I)=(V(I)+THETA*(C(I)*V(I-1)-V(I)*C(I-1)))
     1 /(1.0+THETA*(V(I)-V(I-1)+C(I)-C(I-1)))
      CR(I)=(C(I)*(1.0-VR(I)*THETA)+C(I-1)*VR(I)*THETA)
     1 /(1.0+C(I)*THETA-C(I-1)*THETA)
      HR(I)=H(I)-(H(I)-H(I-1))*THETA*(VR(I)+CR(I))
      XR(I)=XN(I)-(VR(I)+CR(I))*DT
    1 CONTINUE
      DO 2 I=1,N
      VS(I)=(V(I)-THETA*(V(I)*C(I+1)-C(I)*V(I+1)))
     1 /(1.0-THETA*(V(I)-V(I+1)-C(I)+C(I+1)))
      CS(I)=(C(I)+VS(I)*THETA*(C(I)-C(I+1)))
     1 /(1.0+THETA*(C(I)-C(I+1)))
      HS(I)=H(I)+THETA*(VS(I)-CS(I))*(H(I)-H(I+1))
      XS(I)=XN(I)+(VS(I)-CS(I))*DT
    2 CONTINUE
      RETURN
      END
C
C
C
C
C
C
C
C
      SUBROUTINE ENTRY(TIME)
C     THIS SUBROUTINE CALCULATES THE UPSTREAM BOUNDARY CONDITIONS
C     AT EACH TIME STEP BASED ON A KNOWN INFLOW PROFILE.
      DOUBLE PRECISION QP(30),QIN(30),TIN(30),VP(15),HP(15),CP(15)
      DOUBLE PRECISION V(15),H(15)
      DOUBLE PRECISION VR(15),HR(15),CR(15),VS(15),HS(15),CS(15),SS(15)
```

```
      DOUBLE PRECISION SR(15),XR(15),XS(15),XM(15),C(15)
      DOUBLE PRECISION TIME
      DOUBLE PRECISION DTO,DT,DX,D,SO,PL,SEO,XK,RM
      DOUBLE PRECISION TMAX
      DOUBLE PRECISION HC,HN
      DOUBLE PRECISION Q,CON,D,UP,DN,AREA,T,PER,HCRIT,HCN
      DOUBLE PRECISION HNORM,HNN,HB,X3,X4,HFLOW,HBB
      COMMON/CM1/DTO,DT,DX,D,SO,PL,SEO,XK,RM
      COMMON/CM2/N,TMAX
      COMMON/CM3/NPTS,QIN,TIN
      COMMON/CM4/V,H,C,VR,HR,CR,XR,SR,VS,HS,CS,XS,SS,XM
      COMMON/CM5/HC,HN
      COMMON/CM6/CP,VP,HP,QP
      G=9.81
      CON=RM**2/SO
      IF(TIME.GT.0.0)CALL INFLOW(TIME,Q)
      IF(TIME.GT.0.0) GOTO 600
      IF(TIME.EQ.0.0)Q=QIN(1)
C     CALCULATION OF CRITICAL DEPTH.
      UP=D
      DN=0.0
      HC=(UP+DN)/2.0
7     CONTINUE
      CALL SHAPE(HC,AREA,T,PER)
      HCRIT=1.0-(Q**2)*T/(G*AREA**3)
      IF(HCRIT)3,4,5
3     DN=HC
      GOTO 6
5     UP=HC
6     HCN=(UP+DN)/2.0
      IF(ABS((HCN-HC)/HC).LE.0.001) GOTO 8
      HC=HCN
      GOTO 7
8     HC=HCN
4     CONTINUE
C     CALCULATION OF NORMAL DEPTH.
      UP=D
      DN=0.0
      HN=(UP+DN)/2.0
9     CONTINUE
      CALL SHAPE(HN,AREA,T,PER)
      HNORM=1.0-(Q**2)*CON/((AREA**3.333)/(PER**1.333))
      IF(HNORM)10,11,12
10    DN=HN
      GOTO 13
12    UP=HN
13    HNN=(UP+DN)/2.0
      IF(ABS((HNN-HN)/HN).LE.0.001) GOTO 14
      HN=HNN
      GOTO 9
14    HN=HNN
11    CONTINUE
      IF(TIME.EQ.0.0) GOTO 500
C
C
C
C     CALCULATION OF BOUNDARY DEPTH.
600   CONTINUE
      UP=D
      DN=0.0
      HB=(UP+DN)/2.0
15    CONTINUE
      CALL SHAPE(HB,AREA,T,PER)
```

```
      X3=G/CS(1)
      X4=VS(1)-G*(SS(1)-S0)*DT-X3*HS(1)
      HFLOW=Q-(X4+X3*HB)*AREA
      IF(HFLOW)16,17,18
16    UP=HB
      GOTO 19
18    DN=HB
19    HBB=(UP+DN)/2.0
      IF(ABS((HBB-HB)/HB).LE.0.001) GOTO 20
      HB=HBB
      GOTO 15
20    HB=HBB
17    CONTINUE
      HP(1)=HB
      VP(1)=X4+X3*HP(1)
      CALL SHAPE(HB,AREA,T,PER)
      QP(1)=AREA*VP(1)*1000.0
      CP(1)=DSQRT(G*AREA/T)
500   CONTINUE
      RETURN
      END
C
C
C
C
C
C
      SUBROUTINE NODAL(N)
      DOUBLE PRECISION QP(30),QIN(30),TIN(30),VP(15),HP(15),CP(15)
      DOUBLE PRECISION V(15),H(15)
      DOUBLE PRECISION VR(15),HR(15),CR(15),VS(15),HS(15),CS(15),SS(15)
      DOUBLE PRECISION SR(15),XR(15),XS(15),XN(15),C(15)
      DOUBLE PRECISION DTO,DT,DX,D,S0,PL,SFO,XK,RM,HC,HNN
      DOUBLE PRECISION G,X1,X3,X2,X4
      COMMON/CM1/DTO,DT,DX,D,S0,PL,SFO,XK,RM
      COMMON/CM3/NPTS,QIN,TIN
      COMMON/CM4/V,H,C,VR,HR,CR,XR,SR,VS,HS,CS,XS,SS,XN
      COMMON/CM5/HC,HN
      COMMON/CM6/QP,VP,HP,CP
C     THIS SUBROUTINE CALCULATES THE FLOW VELOCITY AND DEPTH
C     AND WAVE SPEED AT EACH OF THE NODES BETWEEN THE UPSTREAM
C     AND DOWNSTREAM BOUNDARIES BY SOLUTION OF THE TWO WAVE
C     EQUATIONS.
      G=9.81
      DO 1 I=2,N
      X1=G/CR(I)
      X3=G/CS(I)
      X2=X1*HR(I)+VR(I)-G*(SR(I)-S0)*DT
      X4=VS(I)-X3*HS(I)-G*(SS(I)-S0)*DT
      HP(I)=(X2-X4)/(X1+X3)
      VP(I)=X4+X3*HP(I)
      CALL WAVSPD(HP(I),CP(I))
      CALL SHAPE(HP(I),X1,X3,X4)
      QP(I)=X1*VP(I)*1000.0
1     CONTINUE
      RETURN
      END
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```

```
      SUBROUTINE SOLID(TIME)
      DOUBLE PRECISION QP(30),QIN(30),TIN(30),VP(15),HP(15),CP(15)
      DOUBLE PRECISION V(15),H(15)
      DOUBLE PRECISION VR(15),HR(15),CR(15),VS(15),HS(15),CS(15),SS(15)
      DOUBLE PRECISION FS(2),SR(15),XF(15),XS(15),XN(15),C(15)
      DOUBLE PRECISION DTO,DT,DX,D,SO,PL,SEO,XK,RM,TIME
      DOUBLE PRECISION TMAX,HC,HN,G,SEV,HO,A1,T,PER,X1
      DOUBLE PRECISION X2,SE,U,E,W,Y,Z,Z4,Z3,Z2,Z1,Z0,F
      DOUBLE PRECISION DF,DH,H1,A2,SE2
      COMMON/CM1/DTO,DT,DX,D,SO,PL,SEO,XK,RM
      COMMON/CM2/N,TMAX
      COMMON/CM3/NPTS,QIN,TIN
      COMMON/CM4/V,H,C,VR,HR,CR,XR,SR,VS,HS,CS,XS,SS,XN
      COMMON/CM5/HC,HN
      COMMON/CM6/QP,VP,HP,CP
C     THIS SUBROUTINE CALCULATES THE FLOW DEPTH, LEAKAGE RATE AND
C     WAVE SPEED AT THE DOWNSTREAM BOUNDARY FORMED BY AN INITIALLY
C     STATIONARY SOLID.
      G=9.81
      IZ=0
      SEV=SEO
      J=1
      HO=H(N+1)
60    CONTINUE
      J=1
3000  CALL SHAPE(HO,A1,T,PER)
      X1=G/CR(N+1)
      X2=X1*HR(N+1)+VR(N+1)-G*(SR(N+1)-SO)*DT
      SE=H(N+1)+(V(N+1)**2)/(2.0*G)
      IF(SE.LT.SEO) GOTO 5
65    CONTINUE
      U=X2*A1/XK
      B=X1*A1/XK
      W=(X1**2)/(2.0*G)
      Y=(X2**2)/(2.0*G)-SEO
      Z=(1.0-X2*X1/G)
      Z4=W**2
      Z3=2.0*W*Z
      Z2=Z**2+2.0*W*Y
      Z1=2.0*Y*Z+B
      Z0=Y**2-U
      F=Z4*HO**4+Z3*HO**3+Z2*HO**2+Z1*HO+Z0
      FS(J)=F
      IF(J.EQ.2) GOTO 7000
      J=2
      HO=HO+0.0001*HO
      GOTO 3000
7000  DF=(FS(2)-FS(1))/(HO/10000.0)
      DH=FS(1)/DF
      H1=HO-DH
      IF(ABS((H1-HO)/HO).LE.0.005) GOTO 70
      IF(H1.GT.D)H1=1.1*HO
      HO=H1
      IZ=IZ+1
      IF(IZ.GT.60) TIME=TMAX
      IF(IZ.GT.60) GOTO 301
      IF(IZ.GT.10) GOTO 805
      GOTO 60
70    CALL SHAPE(H1,A2,T,PER)
      IF(ABS((A2-A1)/A1).LE.0.005) GOTO 80
      A1=(A1+A2)/2.0
      HO=H1
      GOTO 65
```

```
30      CONTINUE
        HP(N+1)=H1
        VP(N+1)=X2-X1*H1
        QP(N+1)=VP(N+1)*A2*1000.0
        GOTO 5
6       VP(N+1)=0.0
        HP(N+1)=X2/X1
        QP(N+1)=0.0
        GOTO 5
5       CALL WAVSFD(HP(N+1),CP(N+1))
        SE2=HP(N+1)+(VP(N+1)**2)/(2.0*C)
        IF(SE2.GT.SEO.AND.SE.LT.SEO)GOTO 800
        GOTO 801
800     SEO=SE
        HO=H(N+1)
        GOTO 65
801     CONTINUE
        SEO=SEV
        DT=DTO
        GOTO 806
805     CONTINUE
        TIME=TIME-DT
        DT=DT/2.0
        GOTO 806
806     CONTINUE
        RETURN
        END
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        SUBROUTINE ASSIGN(N)
C       THIS SUBROUTINE SETS UP THE NEW BASE CONDITIONS ALONG THE
C        PIPE IN PREPARATION FOR THE NEXT TIME STEP.
        DOUBLE PRECISION QP(30),QIN(30),TIN(30),VP(15),HP(15),CP(15)
        DOUBLE PRECISION V(15),H(15)
        DOUBLE PRECISION VR(15),HR(15),CR(15),VS(15),HS(15),CS(15),SS(15)
        DOUBLE PRECISION SR(15),XR(15),XS(15),XN(15),C(15)
        COMMON/CM3/NPTS,QIN,TIN
        COMMON/CM4/V,H,C,VR,HR,CR,XR,SR,VS,HS,CS,XS,SS,XN
        COMMON/CM6/QP,VP,HP,CP
        DO 1 I=1,N+1
        V(I)=VP(I)
        H(I)=HP(I)
        C(I)=CP(I)
1       CONTINUE
        RETURN
        END
$BEND
```

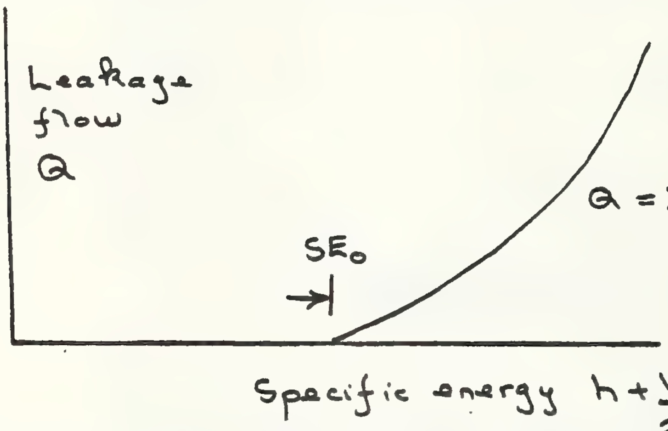
Appendix 2

Derivation of solid boundary equations used in Subroutine SOLID

Derivation of solid boundary equations used in Subroutine SOLID.

Available equations at solid boundary.

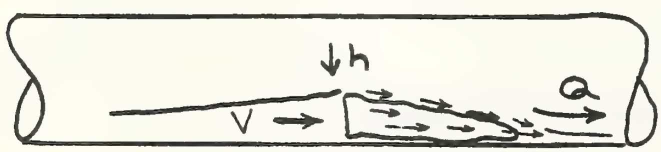
1) <u>Leakage flow past solid:</u>



$Q = XK\{SE - SE_o\}^2$

Note XK, SE_o determined by measurement.

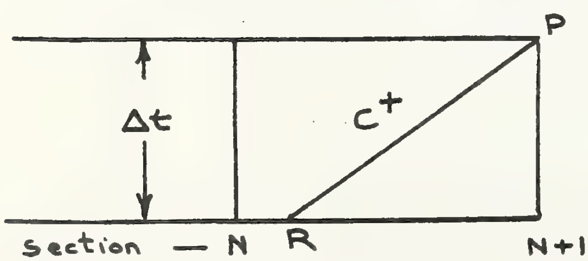
2) <u>Continuity of flow over solid.</u>



$VA = Q$

$A = f(h)$

3) <u>Characteristic equation</u>, C^+ linking R at t to P at $t + \Delta t$.



C^+ equation of form

$V_{N+1} = X2 - X1\ h_{N+1}$

Values of $X1 = g/c_R$

$X2 = V_R + gh_R/c_R - g(S_R - S_o)\Delta t$

From available equations at solid boundary,

$$Q = VA = (X2 - X1\,h)A = XK\{SE - SE_o\}^2$$

$$= XK\left\{h + \frac{V^2}{2g} - SE_o\right\}^2$$

$$(X2 - X1.h)\frac{A}{XK} = \left\{h + (X2 - X1\,h)^2/2g - SE_o\right\}^2$$

$$= \left\{h + (X2^2 + X1^2 h^2 - 2X2.X1.h)/2g - SE_o\right\}^2$$

Collecting terms

$U = X2.A/XK$; $B = X1.A/XK$; $Y = X2^2/2g - SE_o$;

$W = X1^2/2g$; $Z = 1 - 2.X1.X2./2g$

$$\therefore\ U - Bh = \left\{Zh + Y + Wh^2\right\}^2$$

$$= Z^2h^2 + (Y + Wh^2)^2 + 2Zh(Y + Wh^2)$$

$$= Z^2h^2 + Y^2 + W^2h^4 + 2YWh^2 + 2ZYh + 2ZWh^3$$

$$W^2h^4 + 2ZWh^3 + (Z^2 + 2YW)h^2 + (2ZY + B)h + Y^2 - U = 0$$

The quartic in h cannot be solved directly as $A = f(h)$ and therefore B and $U = f(h)$

Solution by Newton Raphson method is acceptable and employed in Subroutine SOLID.

Appendix 3

TRANSCA output

TEST PIPE CONFIGURATION:-
DIAMETER = 0.1000 M. MANNING COEFFICIENT:- 0.0150
PIPE SLOPE = [illegible] PIPE LENGTH = 5.0000 M.

FLOW SUBCRITICAL, NORMAL DEPTH = 0.0189 M. AND CRITICAL DEPTH = 0.0138 M.

INITIAL FLOW RATE = 0.0002 M**3/S. INITIAL DEPTH = 0.0189 M INITIAL WAVE SPEED = 0.3590 M/S.

CALCULATION TIME STEP = 0.2785 S. LENGTH INCREMENT = 0.5000 M. NUMBER OF NODES = 11

		POSITION FROM ENTRY M.	0.	0.5000	1.0000	1.5000	2.0000	2.5000	3.0000	3.5000	4.0000	4.5000	5.0000
TIME =	0. S.	DEPTH M=	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189
		VELOCITY M/S=	0.1945	0.1945	0.1945	0.1945	0.1945	0.1945	0.1945	0.1945	0.1945	0.1945	0.1945
		FLOW RATE L/S=	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000
		WAVE SPD. M/S=	0.3590	0.3590	0.3590	0.3590	0.3590	0.3590	0.3590	0.3590	0.3590	0.3590	0.3590
TIME =	0.279 S.	DEPTH M=	0.0207	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189	0.0256
		VELOCITY M/S=	0.2459	0.1946	0.1946	0.1946	0.1946	0.1946	0.1946	0.1946	0.1946	0.1946	0.0116
		FLOW RATE L/S=	0.2896	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000	0.0184
		WAVE SPD. M/S=	0.3775	0.3590	0.3590	0.3590	0.3590	0.3590	0.3590	0.3590	0.3590	0.3590	0.4220
TIME =	0.557 S.	DEPTH M=	0.0224	0.0194	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189	0.0195	0.0261
		VELOCITY M/S=	0.2668	0.2104	0.1946	0.1946	0.1946	0.1946	0.1946	0.1946	0.1946	0.1762	0.0135
		FLOW RATE L/S=	0.3761	0.2260	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000	0.1904	0.0219
		WAVE SPD. M/S=	0.3937	0.3648	0.3590	0.3590	0.3590	0.3590	0.3590	0.3590	0.3590	0.3657	0.4264
TIME =	0.836 S.	DEPTH M=	0.0241	0.0204	0.0190	0.0189	0.0189	0.0189	0.0189	0.0189	0.0189	0.0202	0.0264
		VELOCITY M/S=	0.3211	0.2351	0.1993	0.1946	0.1946	0.1946	0.1946	0.1946	0.1929	0.1583	0.0149
		FLOW RATE L/S=	0.4677	0.2704	0.2077	0.2000	0.2000	0.2000	0.2000	0.2000	0.1992	0.1802	0.0247
		WAVE SPD. M/S=	0.4088	0.3742	0.3608	0.3590	0.3590	0.3590	0.3590	0.3590	0.3596	0.3727	0.4297
TIME =	1.114 S.	DEPTH M=	0.0257	0.0216	0.0194	0.0189	0.0189	0.0189	0.0189	0.0189	0.0190	0.0210	0.0267
		VELOCITY M/S=	0.3561	0.2643	0.2103	0.1960	0.1946	0.1946	0.1946	0.1944	0.1897	0.1414	0.0160
		FLOW RATE L/S=	0.5577	0.3302	0.2259	0.2023	0.2000	0.2000	0.2000	0.2000	0.1973	0.1693	0.0270
		WAVE SPD. M/S=	0.4229	0.3856	0.3649	0.3595	0.3590	0.3590	0.3590	0.3591	0.3603	0.3797	0.4322
TIME =	1.393 S.	DEPTH M=	0.0272	0.0230	0.0201	0.0191	0.0189	0.0189	0.0189	0.0189	0.0192	0.0217	0.0269
		VELOCITY M/S=	0.3746	0.2948	0.2273	0.2033	0.1950	0.1946	0.1946	0.1940	0.1856	0.1257	0.0169
		FLOW RATE L/S=	0.6467	0.4023	0.2564	0.2072	0.2007	0.2000	0.2000	0.1978	0.1756	0.1578	0.0289
		WAVE SPD. M/S=	0.4363	0.3954	0.3715	0.3611	0.3592	0.3590	0.3590	0.3592	0.3625	0.3866	0.4342
TIME =	1.671 S.	DEPTH M=	0.0286	0.0245	0.0210	0.0194	0.0189	0.0189	0.0189	0.0189	0.0194	0.0224	0.0271
		VELOCITY M/S=	0.3956	0.3243	0.2495	0.2034	0.1965	0.1947	0.1945	0.1933	0.1801	0.1114	0.0177
		FLOW RATE L/S=	0.7346	0.4630	0.2998	0.2229	0.2032	0.2002	0.2000	0.1975	0.1732	0.1462	0.0305
		WAVE SPD. M/S=	0.4490	0.4122	0.3803	0.3643	0.3595	0.3591	0.3590	0.3595	0.3647	0.3930	0.4359
TIME =	1.950 S.	DEPTH M=	0.0301	0.0260	0.0222	0.0199	0.0191	0.0189	0.0189	0.0190	0.0197	0.0230	0.0273
		VELOCITY M/S=	0.4144	0.3514	0.2751	0.2211	0.2001	0.1952	0.1945	0.1922	0.1737	0.0987	0.0184
		FLOW RATE L/S=	[illegible]	0.5691	0.3563	0.2453	0.2047	0.2011	0.2000	0.1970	0.1903	0.1349	0.0320
		WAVE SPD. M/S=	0.4614	0.4257	0.3911	0.3692	0.3611	0.3593	0.3591	0.3589	0.3674	0.3990	0.4374
TIME =	2.228 S.	DEPTH M=	0.0315	0.0275	0.0235	0.0206	0.0193	0.0189	0.0189	0.0190	0.0200	0.0236	0.0274
		VELOCITY M/S=	0.4307	0.3759	0.3023	0.2353	0.2064	0.1967	0.1945	0.1907	0.1663	0.0677	0.0190
		FLOW RATE L/S=	0.9135	0.6591	0.4244	0.2779	0.2174	0.2034	0.2002	0.1933	0.1862	0.1242	0.0333
		WAVE SPD. M/S=	0.4733	0.4390	0.4031	0.3761	0.3635	0.3593	0.3592	0.3636	0.3733	0.4044	0.4387
TIME =	2.507 S.	DEPTH M=	0.0329	0.0290	0.0249	0.0215	0.0197	0.0190	0.0189	0.0191	0.0204	0.0241	0.0276

	VELOCITY	M/S=	0.4442	0.3774	0.3296	0.2577	0.2169	0.1995	0.1797	0.1418	0.1534	0.0773	0.0198
	FLOW RAT	L/S=	0.9062	0.7502	0.5525	0.3221	0.2369	0.2090	0.2010	0.1776	0.1815	0.1144	0.0346
	WAVE SPD.	M/S=	0.4846	0.4511	0.4159	0.3849	0.3671	0.3609	0.3576	0.3614	0.3737	0.4092	0.4399
TIME = 2.785 S.	DEPTH	M=	0.0333	0.0304	0.0263	0.0226	0.0203	0.0192	0.0190	0.0182	0.0208	0.0246	0.0277
	VELOCITY	M/S=	0.4370	0.4159	0.3555	0.2837	0.2275	0.2041	0.1955	0.1564	0.1530	0.0765	0.0201
	FLOW RATE	L/S=	0.9992	0.9403	0.5477	0.3733	0.2613	0.2162	0.2031	0.1768	0.1763	0.1056	0.0357
	WAVE SPD.	M/S=	0.4679	0.4641	0.4290	0.3954	0.3773	0.3624	0.3632	0.3525	0.3775	0.4135	0.4411
TIME = 3.064 S.	DEPTH	M=	0.0337	0.0314	0.0278	0.0237	0.0210	0.0195	0.0171	0.0174	0.0212	0.0250	0.0279
	VELOCITY	M/S=	0.4311	0.4219	0.3791	0.3095	0.2469	0.2118	0.1972	0.1839	0.1413	0.0639	0.0207
	FLOW RATE	L/S=	1.0016	0.9893	0.6769	0.4460	0.2960	0.2292	0.2063	0.1763	0.1714	0.0963	0.0370
	WAVE SPD.	M/S=	0.4911	0.4720	0.4421	0.4071	0.3800	0.3658	0.3613	0.3640	0.3815	0.4172	0.4423
TIME = 3.342 S.	DEPTH	M=	0.0340	0.0320	0.0291	0.0253	0.0219	0.0200	0.0183	0.0176	0.0216	0.0254	0.0280
	VELOCITY	M/S=	0.4253	0.4223	0.3951	0.3354	0.2678	0.2223	0.2001	0.1813	0.1328	0.0586	0.0212
	FLOW RATE	L/S=	1.0016	0.9166	0.7502	0.5234	0.3416	0.2484	0.2124	0.1963	0.1657	0.0919	0.0382
	WAVE SPD.	M/S=	0.4939	0.4777	0.4528	0.4195	0.3847	0.3702	0.3611	0.3559	0.3856	0.4205	0.4434
TIME = 3.621 S.	DEPTH	M=	0.0343	0.0326	0.0301	0.0266	0.0231	0.0206	0.0175	0.0178	0.0220	0.0257	0.0281
	VELOCITY	M/S=	0.4194	0.4199	0.4039	0.3579	0.2913	0.2364	0.2092	0.1770	0.1246	0.0543	0.0218
	FLOW RATE	L/S=	0.9997	0.9319	0.8035	0.6009	0.3983	0.2757	0.2221	0.1974	0.1600	0.0868	0.0395
	WAVE SPD.	M/S=	0.4962	0.4820	0.4612	0.4316	0.3993	0.3761	0.3659	0.3654	0.3873	0.4234	0.4445
TIME = 3.899 S.	DEPTH	M=	0.0346	0.0330	0.0309	0.0278	0.0243	0.0214	0.0199	0.0201	0.0225	0.0260	0.0282
	VELOCITY	M/S=	0.4145	0.4161	0.4076	0.3749	0.3152	0.2539	0.2125	0.1775	0.1171	0.0510	0.0223
	FLOW RATE	L/S=	0.9993	0.9398	0.8397	0.6697	0.4645	0.3123	0.2357	0.2003	0.1549	0.0826	0.0407
	WAVE SPD.	M/S=	0.4986	0.4854	0.4677	0.4421	0.4195	0.3836	0.3678	0.3716	0.3941	0.4260	0.4455
TIME = 4.178 S.	DEPTH	M=	0.0349	0.0333	0.0315	0.0289	0.0255	0.0223	0.0205	0.0205	0.0230	0.0263	0.0284
	VELOCITY	M/S=	0.4102	0.4121	0.4080	0.3861	0.3370	0.2741	0.2226	0.1772	0.1108	0.0486	0.0229
	FLOW RATE	L/S=	1.0005	0.9450	0.8533	0.7250	0.5326	0.3589	0.2577	0.2058	0.1508	0.0800	0.0419
	WAVE SPD.	M/S=	0.5010	0.4884	0.4728	0.4509	0.4217	0.3927	0.3751	0.3756	0.3935	0.4283	0.4466
TIME = 4.456 S.	DEPTH	M=	0.0351	0.0337	0.0320	0.0297	0.0267	0.0234	0.0212	0.0211	0.0235	0.0265	0.0285
	VELOCITY	M/S=	0.4056	0.4083	0.4065	0.3925	0.3548	0.2954	0.2357	0.1786	0.1056	0.0471	0.0234
	FLOW RATE	L/S=	0.9987	0.9494	0.8789	0.7666	0.5967	0.4136	0.2804	0.2150	0.1435	0.0785	0.0432
	WAVE SPD.	M/S=	0.5036	0.4912	0.4769	0.4579	0.4317	0.4027	0.3819	0.3836	0.4030	0.4305	0.4477
TIME = 4.735 S.	DEPTH	M=	0.0349	0.0340	0.0324	0.0304	0.0277	0.0245	0.0221	0.0217	0.0240	0.0268	0.0286
	VELOCITY	M/S=	0.3930	0.4043	0.4041	0.3954	0.3677	0.3159	0.2514	0.1823	0.1028	0.0464	0.0240
	FLOW RATE	L/S=	0.9765	0.9519	0.8961	0.7968	0.6522	0.4726	0.3235	0.2273	0.1403	0.0785	0.0446
	WAVE SPD.	M/S=	0.5014	0.4937	0.4805	0.4635	0.4409	0.4130	0.3911	0.3868	0.4078	0.4327	0.4469
TIME = 5.014 S.	DEPTH	M=	0.0346	0.0341	0.0328	0.0309	0.0286	0.0256	0.0231	0.0225	0.0245	0.0270	0.0288
	VELOCITY	M/S=	0.3797	0.3964	0.4013	0.3960	0.3766	0.3337	0.2634	0.1888	0.1021	0.0460	0.0247
	FLOW RATE	L/S=	0.9173	0.9361	0.8751	0.8137	0.6971	0.5311	0.3651	0.2437	0.1527	0.0802	0.0482
	WAVE SPD.	M/S=	0.4990	0.4943	0.4836	0.4684	0.4483	0.4228	0.3974	0.3942	0.4130	0.4349	0.4511
TIME = 5.292 S.	DEPTH	M=	0.0343	0.0340	0.0330	0.0314	0.0293	0.0267	0.0241	0.0234	0.0252	0.0273	0.0289
	VELOCITY	M/S=	0.3665	0.3863	0.3962	0.3953	0.3815	0.3479	0.2682	0.1979	0.1040	0.0484	0.0255
	FLOW RAT	L/S=	0.8735	0.9091	0.8758	0.8149	0.7322	0.5843	0.4132	0.2772	0.1614	0.0840	0.0482
	WAVE SPD.	M/S=	0.4982	0.4937	0.4856	0.4724	0.4546	0.4318	0.4072	0.4027	0.4147	0.4374	0.4515
TIME = 5.571 S.	DEPTH	M=	0.0339	0.0334	0.0331	0.0318	0.0299	0.0276	0.0252	0.0245	0.0257	0.0276	0.0291
	VELOCITY	M/S=	0.3533	0.3751	0.3890	0.3927	0.3845	0.3583	0.3023	0.2074	0.1090	0.0513	0.0265
	FLOW RAT	L/S=	0.8219	0.8764	0.9332	0.8432	0.7512	0.5312	0.4732	0.3119	0.1755	0.0907	0.0504
	WAVE SPD.	M/S=	0.4931	0.4932	0.4864	0.4758	0.4577	0.4397	0.4181	0.4123	0.4250	0.4403	0.4533
TIME = 5.849 S.	DEPTH	M=	0.0335	0.0335	0.0331	0.0320	0.0304	0.0284	0.0264	0.0256	0.0267	0.0280	0.0294
	VELOCITY	M/S=	0.3406	0.3635	0.3803	0.3862	0.3849	0.3654	0.3180	0.2221	0.1170	0.0559	0.0276
	FLOW RAT	L/S=	0.7837	0.8605	0.8628	0.8427	0.7732	0.6695	0.5206	0.3526	0.1970	0.1006	0.0532
	WAVE SPD.	M/S=	0.4895	0.4901	0.4863	0.4777	0.4643	0.4466	0.4285	0.4224	0.4321	0.4437	0.4554

TIME = 6.124 S.	DEPTH M=	0.0330	0.0332	0.0330	0.0322	0.0308	0.0290	0.0271	0.0268	0.0276	0.0285	0.0297
	VELOCITY M/S=	0.3275	0.3517	0.3706	0.3819	0.3832	0.3695	0.3257	0.2151	0.1277	0.0623	0.0291
	FLOW RATE L/S=	0.7414	0.8027	0.8371	0.8342	0.7899	0.6797	0.5636	0.3972	0.2253	0.1151	0.0570
	WAVE SPD. M/S=	0.4156	0.4475	0.4554	0.4759	0.4670	0.4524	0.4370	0.4326	0.4397	0.4479	0.4581
TIME = 6.406 S.	DEPTH M=	0.0325	0.0329	0.0328	0.0322	0.0311	0.0296	0.0281	0.0279	0.0286	0.0291	0.0301
	VELOCITY M/S=	0.3138	0.3490	0.3603	0.3744	0.3715	0.3710	0.3344	0.2473	0.1406	0.0766	0.0311
	FLOW RATE L/S=	0.6945	0.7652	0.8078	0.8191	0.7916	0.7215	0.6052	0.4429	0.2602	0.1342	0.0620
	WAVE SPD. M/S=	0.4814	0.4847	0.4839	0.4792	0.4700	0.4572	0.4447	0.4426	0.4433	0.4529	0.4616
TIME = 6.685 S.	DEPTH M=	0.0320	0.0325	0.0326	0.0322	0.0313	0.0301	0.0289	0.0290	0.0296	0.0298	0.0306
	VELOCITY M/S=	0.3000	0.3290	0.3499	0.3660	0.3743	0.3701	0.3331	0.2578	0.1547	0.0808	0.0336
	FLOW RATE L/S=	0.6565	0.7258	0.7768	0.7990	0.7872	0.7352	0.6344	0.4869	0.3005	0.1586	0.0686
	WAVE SPD. M/S=	0.4770	0.4814	0.4820	0.4738	0.4715	0.4610	0.4513	0.4519	0.4567	0.4589	0.4660
TIME = 6.963 S.	DEPTH M=	0.0314	0.0321	0.0323	0.0321	0.0314	0.0304	0.0296	0.0300	0.0306	0.0306	0.0313
	VELOCITY M/S=	0.2874	0.3160	0.3392	0.3570	0.3673	0.3673	0.3410	0.2662	0.1690	0.0924	0.0368
	FLOW RATE L/S=	0.6058	0.6866	0.7440	0.7757	0.7760	0.7414	0.6627	0.5266	0.3441	0.1883	0.0774
	WAVE SPD. M/S=	0.4721	0.4778	0.4797	0.4779	0.4724	0.4639	0.4570	0.4602	0.4655	0.4658	0.4715
TIME = 7.242 S.	DEPTH M=	0.0307	0.0316	0.0320	0.0319	0.0314	0.0307	0.0301	0.0308	0.0316	0.0315	0.0321
	VELOCITY M/S=	0.2735	0.3040	0.3284	0.3475	0.3605	0.3628	0.3405	0.2721	0.1823	0.1048	0.0409
	FLOW RATE L/S=	0.5605	0.6472	0.7104	0.7499	0.7613	0.7409	0.6772	0.5603	0.3881	0.2226	0.0889
	WAVE SPD. M/S=	0.4666	0.4740	0.4770	0.4765	0.4725	0.4661	0.4616	0.4676	0.4739	0.4735	0.4761
TIME = 7.520 S.	DEPTH M=	0.0301	0.0311	0.0316	0.0317	0.0314	0.0308	0.0306	0.0316	0.0325	0.0325	0.0330
	VELOCITY M/S=	0.2602	0.2917	0.3175	0.3377	0.3524	0.3570	0.3379	0.2756	0.1940	0.1173	0.0457
	FLOW RATE L/S=	0.5160	0.6074	0.6762	0.7223	0.7434	0.7347	0.6883	0.5869	0.4303	0.2601	0.1035
	WAVE SPD. M/S=	0.4614	0.4697	0.4740	0.4747	0.4722	0.4676	0.4657	0.4740	0.4817	0.4818	0.4859
TIME = 7.799 S.	DEPTH M=	0.0294	0.0306	0.0312	0.0314	0.0313	0.0309	0.0310	0.0322	0.0334	0.0336	0.0341
	VELOCITY M/S=	0.2452	0.2796	0.3065	0.3241	0.3437	0.3502	0.3335	0.2769	0.2034	0.1290	0.0514
	FLOW RATE L/S=	0.4716	0.5665	0.6415	0.6935	0.7223	0.7240	0.6910	0.6062	0.4672	0.2987	0.1216
	WAVE SPD. M/S=	0.4552	0.4653	0.4707	0.4726	0.4714	0.4684	0.4688	0.4773	0.4838	0.4904	0.4947
TIME = 8.077 S.	DEPTH M=	0.0286	0.0300	0.0308	0.0311	0.0311	0.0310	0.0313	0.0328	0.0342	0.0347	0.0353
	VELOCITY M/S=	0.2307	0.2669	0.2955	0.3191	0.3351	0.3425	0.3277	0.2761	0.2102	0.1390	0.0578
	FLOW RATE L/S=	0.4285	0.5285	0.6066	0.6638	0.6973	0.7097	0.6830	0.6184	0.4981	0.3360	0.1430
	WAVE SPD. M/S=	0.4490	0.4604	0.4671	0.4701	0.4732	0.4688	0.4713	0.4837	0.4950	0.4991	0.5042
TIME = 8.356 S.	DEPTH M=	0.0276	0.0294	0.0303	0.0308	0.0310	0.0310	0.0315	0.0332	0.0348	0.0357	0.0365
	VELOCITY M/S=	0.2144	0.2542	0.2843	0.3061	0.3260	0.3341	0.3298	0.2737	0.2144	0.1469	0.0646
	FLOW RATE L/S=	0.3822	0.4692	0.5717	0.6337	0.6744	0.6927	0.6834	0.6241	0.5217	0.3697	0.1675
	WAVE SPD. M/S=	0.4418	0.4553	0.4633	0.4674	0.4686	0.4688	0.4732	0.4873	0.5005	0.5075	0.5141
TIME = 8.634 S.	DEPTH M=	0.0270	0.0287	0.0298	0.0305	0.0307	0.0309	0.0317	0.0336	0.0354	0.0367	0.0377
	VELOCITY M/S=	0.1964	0.2407	0.2729	0.2950	0.3167	0.3256	0.3130	0.2637	0.2160	0.1524	0.0715
	FLOW RATE L/S=	0.3391	0.4490	0.5366	0.6030	0.6473	0.6734	0.6670	0.6241	0.5377	0.3978	0.1941
	WAVE SPD. M/S=	0.4346	0.4497	0.4591	0.4644	0.4653	0.4684	0.4747	0.4903	0.5053	0.5155	0.5240
TIME = 8.913 S.	DEPTH M=	0.0262	0.0280	0.0293	0.0301	0.0305	0.0309	0.0318	0.0339	0.0359	0.0376	0.0389
	VELOCITY M/S=	0.1665	0.2271	0.2513	0.2877	0.3073	0.3166	0.3046	0.2645	0.2153	0.1553	0.0783
	FLOW RATE L/S=	0.2937	0.4095	0.5012	0.5721	0.6221	0.6524	0.6546	0.6173	0.5436	0.4192	0.2215
	WAVE SPD. M/S=	0.4264	0.4430	0.4547	0.4612	0.4667	0.4678	0.4758	0.4927	0.5095	0.5229	0.5333
TIME = 9.192 S.	DEPTH M=	0.0251	0.0273	0.0287	0.0297	0.0302	0.0306	0.0319	0.0341	0.0364	0.0384	0.0400
	VELOCITY M/S=	0.1617	0.2124	0.2494	0.2773	0.2977	0.3072	0.2936	0.2532	0.2125	0.1559	0.0847
	FLOW RATE L/S=	0.2494	0.3699	0.4558	0.5438	0.5954	0.6300	0.6371	0.6133	0.5455	0.4336	0.2415
	WAVE SPD. M/S=	0.4177	0.4375	0.4499	0.4575	0.4624	0.4667	0.4755	0.4946	0.5131	0.5295	0.5419
TIME = 9.470 S.	DEPTH M=	0.0240	0.0265	0.0282	0.0292	0.0297	0.0306	0.0320	0.0343	0.0368	0.0392	0.0410
	VELOCITY M/S=	0.1410	0.1978	0.2372	0.2607	0.2877	0.2976	0.2862	0.2510	0.2010	0.1547	0.0964

	FLOW RAT	L/S=	[illegible]	[illegible]	0.4164	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.4411	0.2727
	WAVE SPD.	M/S=	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.4771	[illegible]	[illegible]	[illegible]	[illegible]
TIME = 9.749 S.	DEPTH	M=	0.0231	0.0257	0.0275	0.0297	[illegible]	0.0305	0.0320	0.0345	0.0372	0.0390	0.0418
	VELOCITY	M/S=	0.1394	0.1920	0.2246	0.2533	0.2777	0.2877	0.2754	0.2430	0.2017	0.1519	0.0953
	FLOW RAT.	L/S=	0.1999	0.2906	0.3750	0.4777	0.5404	0.5823	0.5911	0.5327	0.5165	0.4430	0.2961
	WAVE SPD.	M/S=	0.4159	0.4234	0.4394	0.4499	0.4571	0.4645	0.4772	0.4975	0.5143	0.5405	0.5559
TIME = 10.027 S.	DEPTH	M=	0.0230	0.0251	0.0269	0.0282	0.0283	0.0303	0.0320	0.0340	0.0375	0.0404	0.0424
	VELOCITY	M/S=	0.1401	0.1715	0.2116	0.2447	0.2677	0.2775	0.2663	0.2343	0.1747	0.1401	0.0993
	FLOW RATE	L/S=	0.1996	0.2651	0.3597	0.4460	0.5122	0.5573	0.5767	0.5630	0.5235	0.4398	0.3151
	WAVE SPD.	M/S=	0.4045	0.4161	0.4337	0.4456	0.4542	0.4630	0.4772	0.4936	0.5220	0.5446	0.5611
TIME = 10.306 S.	DEPTH	M=	0.0235	0.0247	0.0263	0.0277	0.0287	0.0301	0.0320	0.0347	0.0376	0.0406	0.0429
	VELOCITY	M/S=	0.1423	0.1650	0.2000	0.2333	0.2572	0.2671	0.2556	0.2250	0.1865	0.1436	0.1025
	FLOW RATE	L/S=	0.2062	0.2489	0.3294	0.4142	0.4836	0.5317	0.5517	0.5451	0.5071	0.4326	0.3304
	WAVE SPD.	M/S=	0.4034	0.4142	0.4264	0.4411	0.4511	0.4614	0.4771	0.4937	0.5244	0.5484	0.5652
TIME = 10.584 S.	DEPTH	M=	0.0234	0.0244	0.0258	0.0272	0.0285	0.0299	0.0319	0.0348	0.0381	0.0412	0.0433
	VELOCITY	M/S=	0.1431	0.1612	0.1906	0.2222	0.2464	0.2563	0.2450	0.2150	0.1778	0.1388	0.1048
	FLOW RATE	L/S=	0.1995	0.2386	0.3053	0.3842	0.4548	0.5054	0.5277	0.5233	0.4880	0.4231	0.3419
	WAVE SPD.	M/S=	0.4021	0.4113	0.4238	0.4366	0.4478	0.4596	0.4769	0.5006	0.5265	0.5512	0.5682
TIME = 10.863 S.	DEPTH	M=	0.0232	0.0241	0.0253	0.0267	0.0281	0.0297	0.0319	0.0349	0.0383	0.0414	0.0436
	VELOCITY	M/S=	0.1443	0.1588	0.1833	0.2120	0.2356	0.2453	0.2339	0.2045	0.1687	0.1338	0.1065
	FLOW RATE	L/S=	0.1997	0.2315	0.2868	0.3576	0.4265	0.4787	0.5047	0.4998	0.4668	0.4114	0.3501
	WAVE SPD.	M/S=	0.4009	0.4089	0.4200	0.4324	0.4444	0.4578	0.4765	0.5014	0.5284	0.5533	0.5703
TIME = 11.141 S.	DEPTH	M=	0.0231	0.0239	0.0250	0.0263	0.0277	0.0294	0.0319	0.0350	0.0385	0.0416	0.0438
	VELOCITY	M/S=	0.1454	0.1574	0.1778	0.2030	0.2250	0.2340	0.2224	0.1936	0.1594	0.1289	0.1075
	FLOW RATE	L/S=	0.1997	0.2268	0.2726	0.3347	0.3936	0.4510	0.4738	0.4749	0.4442	0.3986	0.3551
	WAVE SPD.	M/S=	0.3998	0.4070	0.4169	0.4286	0.4411	0.4558	0.4761	0.5022	0.5300	0.5546	0.5715
TIME = 11.420 S.	DEPTH	M=	0.0230	0.0237	0.0247	0.0259	0.0274	0.0292	0.0318	0.0351	0.0387	0.0417	0.0438
	VELOCITY	M/S=	0.1464	0.1568	0.1736	0.1953	0.2150	0.2226	0.2105	0.1822	0.1501	0.1241	0.1080
	FLOW RATE	L/S=	0.1996	0.2235	0.2619	0.3156	0.3749	0.4252	0.4522	0.4486	0.4207	0.3851	0.3576
	WAVE SPD.	M/S=	0.3987	0.4054	0.4142	0.4252	0.4380	0.4539	0.4757	0.5030	0.5313	0.5556	0.5721
TIME = 11.698 S.	DEPTH	M=	0.0229	0.0236	0.0244	0.0256	0.0271	0.0290	0.0318	0.0352	0.0388	0.0418	0.0438
	VELOCITY	M/S=	0.1470	0.1565	0.1705	0.1883	0.2050	0.2113	0.1983	0.1706	0.1410	0.1194	0.1080
	FLOW RATE	L/S=	0.2004	0.2210	0.2537	0.2937	0.3527	0.3995	0.4251	0.4214	0.3967	0.3712	0.3577
	WAVE SPD.	M/S=	0.3976	0.4040	0.4120	0.4224	0.4353	0.4521	0.4753	0.5036	0.5322	0.5560	0.5722
TIME = 11.977 S.	DEPTH	M=	0.0228	0.0234	0.0242	0.0253	0.0268	0.0288	0.0317	0.0353	0.0388	0.0418	0.0438
	VELOCITY	M/S=	0.1482	0.1567	0.1683	0.1833	0.1969	0.2001	0.1859	0.1590	0.1322	0.1150	0.1076
	FLOW RATE	L/S=	0.1998	0.2195	0.2473	0.2867	0.3331	0.3751	0.3978	0.3935	0.3728	0.3573	0.3559
	WAVE SPD.	M/S=	0.3966	0.4027	0.4102	0.4290	0.4328	0.4505	0.4749	0.5041	0.5327	0.5556	0.5717
TIME = 12.255 S.	DEPTH	M=	0.0227	0.0233	0.0241	0.0251	0.0266	0.0287	0.0317	0.0353	0.0387	0.0417	0.0437
	VELOCITY	M/S=	0.1496	0.1569	0.1666	0.1747	0.1930	0.1893	0.1735	0.1473	0.1236	0.1108	0.1070
	FLOW RATE	L/S=	0.2003	0.2181	0.2425	0.2760	0.3157	0.3522	0.3738	0.3654	0.3493	0.3433	0.3524
	WAVE SPD.	M/S=	0.3957	0.4016	0.4086	0.4190	0.4303	0.4492	0.4746	0.5045	0.5323	0.5552	0.5709
TIME = 12.534 S.	DEPTH	M=	0.0226	0.0232	0.0239	0.0249	0.0264	0.0286	0.0317	0.0354	0.0388	0.0416	0.0435
	VELOCITY	M/S=	0.1509	0.1573	0.1654	0.1748	0.1914	0.1783	0.1612	0.1359	0.1158	0.1066	0.1060
	FLOW RAT	L/S=	0.2005	0.2171	0.2366	0.2672	0.3038	0.3308	0.3444	0.3378	0.3264	0.3295	0.3477
	WAVE SPD.	M/S=	0.3948	0.4005	0.4073	0.4153	0.4272	0.4482	0.4746	0.5048	0.5326	0.5542	0.5697
TIME = 12.812 S.	DEPTH	M=	0.0224	0.0231	0.0238	0.0248	0.0262	0.0285	0.0317	0.0354	0.0386	0.0414	0.0433
	VELOCITY	M/S=	0.1513	0.1577	0.1644	0.1714	0.1751	0.1687	0.1472	0.1250	0.1033	0.1029	0.1047
	FLOW RATE	L/S=	0.1997	0.2161	0.2354	0.2598	0.2876	0.3111	0.3119	0.3107	0.3045	0.3159	0.3416
	WAVE SPD.	M/S=	0.3937	0.3995	0.4061	0.4155	0.4230	0.4476	0.4747	0.5049	0.5321	0.5529	0.5662

TIME													
TIME = 13.091 S.	DEPTH	M=	0.0224	0.0230	0.0237	0.0247	0.0261	0.0285	0.0317	0.0354	0.0386	0.0412	0.0431
	VELOCITY	M/S=	[illegible]	0.1580	0.1637	[illegible]	0.1693	0.1590	0.1376	0.1147	0.1013	0.0992	0.1035
	FLOW RAT	L/S=	0.2005	0.2153	[illegible]	0.2535	0.2757	0.2927	0.2945	0.2350	0.2830	0.3026	0.3351
	WAVE SPD.	M/S=	0.3930	0.3986	0.4051	0.4137	0.4271	0.4474	0.4749	0.5050	0.5312	0.5514	0.5664
TIME = 13.369 S.	DEPTH	M=	0.0223	0.0229	0.0236	0.0246	0.0261	0.0285	0.0318	0.0354	0.0385	0.0410	0.0428
	VELOCITY	M/S=	0.1535	0.1545	0.1630	0.1677	0.1627	0.1496	0.1255	0.1031	0.0949	0.0957	0.1019
	FLOW RATE	L/S=	0.2002	0.2147	0.2305	0.2482	0.2655	0.2756	0.2715	0.2610	0.2646	0.2896	0.3276
	WAVE SPD.	M/S=	0.3921	0.3977	0.4042	0.4131	0.4267	0.4475	0.4734	0.5049	0.5301	0.5495	0.5644
TIME = 13.648 S.	DEPTH	M=	0.0222	0.0228	0.0235	0.0245	0.0261	0.0285	0.0318	0.0353	0.0383	0.0407	0.0426
	VELOCITY	M/S=	0.1541	0.1588	0.1623	0.1631	0.1572	0.1406	0.1161	0.0963	0.0891	0.0923	0.1003
	FLOW RATE	L/S=	0.1998	0.2140	0.2285	0.2434	0.2560	0.2597	0.2479	0.2370	0.2469	0.2772	0.3155
	WAVE SPD.	M/S=	0.3912	0.3969	0.4035	0.4125	0.4265	0.4460	0.4760	0.5046	0.5236	0.5475	0.5623
TIME = 13.927 S.	DEPTH	M=	0.0221	0.0227	0.0234	0.0245	0.0261	0.0286	0.0319	0.0353	0.0382	0.0404	0.0423
	VELOCITY	M/S=	0.1552	0.1591	0.1617	0.1606	0.1517	0.1319	0.1065	0.0884	0.0838	0.0891	0.0985
	FLOW RATE	L/S=	0.2002	0.2132	0.2266	0.2390	0.2472	0.2447	0.2299	0.2130	0.2307	0.2653	0.3111
	WAVE SPD.	M/S=	0.3905	0.3961	0.4028	0.4122	0.4267	0.4487	0.4766	0.5043	0.5273	0.5454	0.5600
TIME = 14.205 S.	DEPTH	M=	0.0220	0.0226	0.0234	0.0244	0.0261	0.0287	0.0320	0.0352	0.0379	0.0401	0.0420
	VELOCITY	M/S=	0.1562	0.1594	0.1610	0.1580	0.1462	0.1236	0.0976	0.0815	0.0792	0.0862	0.0967
	FLOW RATE	L/S=	0.2005	0.2126	0.2248	0.2349	0.2390	0.2306	0.2115	0.2014	0.2165	0.2541	0.3025
	WAVE SPD.	M/S=	0.3896	0.3954	0.4023	0.4120	0.4272	0.4498	0.4774	0.5038	0.5257	0.5431	0.5577
TIME = 14.484 S.	DEPTH	M=	0.0219	0.0226	0.0233	0.0244	0.0262	0.0289	0.0321	0.0352	0.0377	0.0399	0.0417
	VELOCITY	M/S=	0.1564	0.1596	0.1602	0.1553	0.1407	0.1156	0.0875	0.0754	0.0752	0.0835	0.0948
	FLOW RATE	L/S=	0.1995	0.2120	0.2230	0.2310	0.2311	0.2173	0.1950	0.1859	0.2039	0.2437	0.2937
	WAVE SPD.	M/S=	0.3889	0.3948	0.4018	0.4120	0.4277	0.4510	0.4736	0.5033	0.5240	0.5408	0.5552
TIME = 14.762 S.	DEPTH	M=	0.0219	0.0225	0.0233	0.0245	0.0263	0.0290	0.0322	0.0351	0.0375	0.0396	0.0414
	VELOCITY	M/S=	0.1576	0.1597	0.1593	0.1526	0.1352	0.1081	0.0825	0.0703	0.0717	0.0810	0.0929
	FLOW RATE	L/S=	0.2005	0.2111	0.2213	0.2271	0.2233	0.2047	0.1802	0.1727	0.1929	0.2341	0.2850
	WAVE SPD.	M/S=	0.3884	0.3941	0.4015	0.4122	0.4233	0.4524	0.4780	0.5027	0.5222	0.5385	0.5528
TIME = 15.041 S.	DEPTH	M=	0.0218	0.0224	0.0233	0.0245	0.0265	0.0292	0.0323	0.0350	0.0373	0.0393	0.0411
	VELOCITY	M/S=	0.1581	0.1598	0.1582	0.1496	0.1297	0.1010	0.0763	0.0659	0.0687	0.0787	0.0910
	FLOW RATE	L/S=	0.2002	0.2106	0.2194	0.2233	0.2157	0.1929	0.1672	0.1616	0.1835	0.2253	0.2765
	WAVE SPD.	M/S=	0.3877	0.3936	0.4012	0.4126	0.4301	0.4539	0.4775	0.5019	0.5205	0.5362	0.5503
TIME = 15.319 S.	DEPTH	M=	0.0217	0.0224	0.0232	0.0246	0.0266	0.0294	0.0323	0.0349	0.0371	0.0390	0.0407
	VELOCITY	M/S=	0.1585	0.1598	0.1571	0.1464	0.1241	0.0944	0.0710	0.0624	0.0663	0.0767	0.0892
	FLOW RATE	L/S=	0.1997	0.2099	0.2176	0.2173	0.2082	0.1819	0.1560	0.1524	0.1756	0.2175	0.2682
	WAVE SPD.	M/S=	0.3870	0.3932	0.4011	0.4131	0.4314	0.4554	0.4801	0.5012	0.5187	0.5339	0.5479
TIME = 15.598 S.	DEPTH	M=	0.0217	0.0223	0.0232	0.0246	0.0268	0.0296	0.0324	0.0348	0.0369	0.0387	0.0404
	VELOCITY	M/S=	0.1593	0.1596	0.1557	0.1430	0.1116	0.0884	0.0665	0.0576	0.0643	0.0750	0.0874
	FLOW RATE	L/S=	0.2000	0.2090	0.2157	0.2152	0.2037	0.1717	0.1435	0.1450	0.1671	0.2105	0.2663
	WAVE SPD.	M/S=	0.3866	0.3927	0.4011	0.4138	0.4330	0.4570	0.4805	0.5004	0.5173	0.5317	0.5455
TIME = 15.876 S.	DEPTH	M=	0.0216	0.0223	0.0233	0.0247	0.0270	0.0298	0.0324	0.0347	0.0367	0.0384	0.0402
	VELOCITY	M/S=	0.1595	0.1594	0.1541	0.1374	0.1130	0.0829	0.0623	0.0575	0.0628	0.0735	0.0857
	FLOW RATE	L/S=	0.2002	0.2083	0.2137	0.2110	0.1932	0.1624	0.1316	0.1372	0.1638	0.2043	0.2527
	WAVE SPD.	M/S=	0.3861	0.3924	0.4012	0.4147	0.4346	0.4584	0.4837	0.4995	0.5153	0.5296	0.5432
TIME = 16.155 S.	DEPTH	M=	0.0216	0.0223	0.0233	0.0249	0.0272	0.0299	0.0325	0.0346	0.0365	0.0382	0.0399
	VELOCITY	M/S=	0.1603	0.1591	0.1524	0.1356	0.1075	0.0790	0.0577	0.0559	0.0617	0.0722	0.0840
	FLOW RATE	L/S=	0.2000	0.2075	0.2116	0.2066	0.1853	0.1540	0.1323	0.1349	0.1577	0.1989	0.2455
	WAVE SPD.	M/S=	0.3856	0.3921	0.4014	0.4156	0.4353	0.4577	0.4812	0.4977	0.5137	0.5275	0.5410
TIME = 16.433 S.	DEPTH	M=	0.0215	0.0223	0.0233	0.0250	0.0274	0.0301	0.0325	0.0345	0.0363	0.0379	0.0396
	VELOCITY	M/S=	0.1606	0.1587	0.1504	0.1316	0.1024	0.0736	0.0576	0.0549	0.0609	0.0711	0.0825
	FLOW RAT	L/S=	0.1987	0.2067	0.2094	0.2020	0.1736	0.1466	0.1273	0.1318	0.1565	0.1943	0.2318

	WAVE SPD.	M/S=	0.3852	0.3920	0.4018	0.4169	0.4340	0.4611	0.4813	0.4978	0.5121	0.5256	0.5389
TIME = 16.712 S.	DEPTH	M=	0.0215	0.0223	0.0234	0.0251	0.0276	0.0302	0.0325	0.0344	0.0361	0.0377	0.0394
	VELOCITY	M/S=	0.1614	0.1540	0.1403	0.1275	0.0974	0.0701	0.0557	0.0543	0.0604	0.0702	0.0810
	FLOW RATE	L/S=	0.2004	0.2057	0.2070	0.1972	0.1715	0.1403	0.1237	0.1278	0.1543	0.1904	0.2326
	WAVE SPD.	M/S=	0.3850	0.3919	0.4023	0.4183	0.4377	0.4622	0.4813	0.4969	0.5136	0.5237	0.5369
TIME = 16.990 S.	DEPTH	M=	0.0215	0.0223	0.0234	0.0253	0.0273	0.0303	0.0325	0.0343	0.0359	0.0375	0.0391
	VELOCITY	M/S=	0.1617	0.1571	0.1459	0.1232	0.0927	0.0671	0.0548	0.0541	0.0603	0.0696	0.0796
	FLOW RATE	L/S=	0.2004	0.2049	0.2045	0.1923	0.1647	0.1349	0.1212	0.1288	0.1529	0.1870	0.2219
	WAVE SPD.	M/S=	0.3847	0.3917	0.4029	0.4177	0.4414	0.4632	0.4812	0.4960	0.5092	0.5220	0.5351
TIME = 17.269 S.	DEPTH	M=	0.0215	0.0223	0.0235	0.0255	0.0279	0.0304	0.0325	0.0342	0.0357	0.0373	0.0389
	VELOCITY	M/S=	0.1616	0.1565	0.1433	0.1157	0.0834	0.0646	0.0542	0.0543	0.0603	0.0690	0.0784
	FLOW RATE	L/S=	0.2003	0.2040	0.2019	0.1873	0.1547	0.1305	0.1177	0.1236	0.1519	0.1643	0.2216
	WAVE SPD.	M/S=	0.3845	0.3920	0.4036	0.4212	0.4430	0.4640	0.4811	0.4951	0.5074	0.5204	0.5334
TIME = 17.547 S.	DEPTH	M=	0.0214	0.0223	0.0236	0.0256	0.0281	0.0305	0.0324	0.0341	0.0356	0.0371	0.0387
	VELOCITY	M/S=	0.1618	0.1555	0.1405	0.1146	0.0844	0.0627	0.0539	0.0547	0.0605	0.0687	0.0772
	FLOW RATE	L/S=	0.1999	0.2030	0.1991	0.1823	0.1527	0.1271	0.1170	0.1270	0.1515	0.1820	0.2168
	WAVE SPD.	M/S=	0.3843	0.3922	0.4045	0.4227	0.4445	0.4647	0.4808	0.4942	0.5065	0.5189	0.5318
TIME = 17.826 S.	DEPTH	M=	0.0214	0.0223	0.0237	0.0258	0.0283	0.0305	0.0324	0.0339	0.0354	0.0369	0.0385
	VELOCITY	M/S=	0.1621	0.1543	0.1376	0.1103	0.0810	0.0613	0.0541	0.0553	0.0609	0.0684	0.0760
	FLOW RATE	L/S=	0.2002	0.2018	0.1963	0.1773	0.1478	0.1245	0.1171	0.1300	0.1518	0.1802	0.2122
	WAVE SPD.	M/S=	0.3843	0.3925	0.4055	0.4243	0.4457	0.4652	0.4805	0.4934	0.5053	0.5175	0.5303
TIME = 18.104 S.	DEPTH	M=	0.0214	0.0224	0.0239	0.0260	0.0284	0.0306	0.0323	0.0338	0.0353	0.0368	0.0384
	VELOCITY	M/S=	0.1621	0.1530	0.1345	0.1063	0.0777	0.0603	0.0545	0.0562	0.0615	0.0682	0.0751
	FLOW RATE	L/S=	0.2002	0.2007	0.1932	0.1724	0.1433	0.1228	0.1179	0.1314	0.1523	0.1787	0.2082
	WAVE SPD.	M/S=	0.3843	0.3927	0.4066	0.4260	0.4472	0.4655	0.4801	0.4925	0.5042	0.5162	0.5290
TIME = 18.383 S.	DEPTH	M=	0.0214	0.0224	0.0240	0.0262	0.0285	0.0306	0.0323	0.0337	0.0352	0.0366	0.0382
	VELOCITY	M/S=	0.1618	0.1515	0.1313	0.1024	0.0754	0.0596	0.0552	0.0571	0.0621	0.0682	0.0742
	FLOW RATE	L/S=	0.1999	0.1995	0.1901	0.1677	0.1395	0.1219	0.1211	0.1332	0.1531	0.1776	0.2046
	WAVE SPD.	M/S=	0.3843	0.3934	0.4079	0.4275	0.4483	0.4658	0.4797	0.4917	0.5032	0.5151	0.5278
TIME = 18.662 S.	DEPTH	M=	0.0215	0.0225	0.0241	0.0264	0.0287	0.0306	0.0322	0.0336	0.0350	0.0365	0.0381
	VELOCITY	M/S=	0.1616	0.1498	0.1280	0.0987	0.0733	0.0596	0.0561	0.0582	0.0625	0.0682	0.0734
	FLOW RATE	L/S=	0.2002	0.1981	0.1870	0.1632	0.1364	0.1216	0.1224	0.1352	0.1541	0.1767	0.2015
	WAVE SPD.	M/S=	0.3845	0.3941	0.4092	0.4291	0.4492	0.4659	0.4772	0.4909	0.5022	0.5140	0.5267
TIME = 18.940 S.	DEPTH	M=	0.0215	0.0226	0.0243	0.0265	0.0288	0.0306	0.0322	0.0336	0.0349	0.0364	0.0379
	VELOCITY	M/S=	0.1615	0.1481	0.1247	0.0954	0.0717	0.0598	0.0572	0.0594	0.0635	0.0682	0.0727
	FLOW RATE	L/S=	0.2002	0.1967	0.1837	0.1591	0.1340	0.1220	0.1248	0.1374	0.1553	0.1761	0.1988
	WAVE SPD.	M/S=	0.3847	0.3944	0.4105	0.4305	0.4500	0.4659	0.4734	0.4901	0.5013	0.5131	0.5256
TIME = 19.219 S.	DEPTH	M=	0.0215	0.0227	0.0244	0.0267	0.0288	0.0306	0.0321	0.0335	0.0348	0.0363	0.0378
	VELOCITY	M/S=	0.1608	0.1462	0.1214	0.0924	0.0705	0.0603	0.0584	0.0606	0.0644	0.0684	0.0721
	FLOW RATE	L/S=	0.1997	0.1953	0.1805	0.1554	0.1323	0.1229	0.1271	0.1378	0.1567	0.1758	0.1962
	WAVE SPD.	M/S=	0.3850	0.3957	0.4119	0.4317	0.4507	0.4659	0.4732	0.4874	0.5005	0.5122	0.5247
TIME = 19.497 S.	DEPTH	M=	0.0216	0.0228	0.0246	0.0268	0.0289	0.0306	0.0320	0.0334	0.0347	0.0362	0.0377
	VELOCITY	M/S=	0.1604	0.1441	0.1183	0.0878	0.0697	0.0610	0.0597	0.0619	0.0652	0.0685	0.0715
	FLOW RATE	L/S=	0.1999	0.1937	0.1774	0.1522	0.1312	0.1242	0.1296	0.1422	0.1581	0.1756	0.1940
	WAVE SPD.	M/S=	0.3854	0.3966	0.4134	0.4332	0.4513	0.4657	0.4777	0.4917	0.4994	0.5114	0.5239
TIME = 19.776 S.	DEPTH	M=	0.0216	0.0229	0.0248	0.0270	0.0290	0.0306	0.0320	0.0333	0.0347	0.0361	0.0376
	VELOCITY	M/S=	0.1597	0.1419	0.1152	0.0876	0.0693	0.0619	0.0611	0.0632	0.0660	0.0687	0.0710
	FLOW RATE	L/S=	0.1996	0.1922	0.1744	0.1474	0.1307	0.1259	0.1323	0.1446	0.1595	0.1755	0.1920
	WAVE SPD.	M/S=	0.3855	0.3977	0.4148	0.4344	0.4517	0.4655	0.4772	0.4881	0.4991	0.5107	0.5232
TIME = 20.054 S.	DEPTH	M=	0.0217	0.0230	0.0249	0.0271	0.0290	0.0306	0.0319	0.0332	0.0346	0.0360	0.0376

	VELOCITY	M/S=	0.1593	0.1377	0.1123	0.0857	0.0692	0.0629	0.0625	0.0645	0.0667	0.0689	0.0706
	FLOW RAT	L/S=	0.2000	0.1909	0.1716	0.1472	0.1335	0.1253	0.1331	0.1471	0.1611	0.1755	0.1882
	WAVE SPD.	M/S=	0.3866	0.3995	0.4163	0.4324	0.4470	0.4654	0.4737	0.4875	0.4985	0.5101	0.5226
TIME = 20.333 S.	DEPTH	M=	0.0216	0.0231	0.0251	0.0272	0.0290	0.0303	0.0317	0.0332	0.0345	0.0359	0.0375
	VELOCITY	M/S=	0.1585	0.1375	0.1096	0.0843	0.0675	0.0642	0.0640	0.0657	0.0677	0.0692	0.0702
	FLOW RAT	L/S=	0.1995	0.1891	0.1669	0.1476	0.1314	0.1303	0.1379	0.1496	0.1625	0.1756	0.1887
	WAVE SPD.	M/S=	0.3873	0.4006	0.4177	0.4353	0.4522	0.4659	0.4761	0.4869	0.4977	0.5095	0.5220
TIME = 20.611 S.	DEPTH	M=	0.0219	0.0233	0.0252	0.0273	0.0290	0.0305	0.0318	0.0331	0.0344	0.0359	0.0374
	VELOCITY	M/S=	0.1579	0.1351	0.1072	0.0832	0.0700	0.0655	0.0655	0.0670	0.0684	0.0694	0.0698
	FLOW RATE	L/S=	0.2005	0.1877	0.1666	0.1444	0.1325	0.1328	0.1417	0.1520	0.1640	0.1758	0.1874
	WAVE SPD.	M/S=	0.3882	0.4013	0.4190	0.4371	0.4523	0.4647	0.4756	0.4863	0.4974	0.5091	0.5215
TIME = 20.890 S.	DEPTH	M=	0.0219	0.0234	0.0254	0.0274	0.0290	0.0304	0.0317	0.0330	0.0344	0.0358	0.0374
	VELOCITY	M/S=	0.1565	0.1333	0.1051	0.0825	0.0707	0.0670	0.0670	0.0682	0.0692	0.0696	0.0695
	FLOW RATE	L/S=	0.1996	0.1865	0.1647	0.1436	0.1337	0.1354	0.1436	0.1544	0.1655	0.1760	0.1862
	WAVE SPD.	M/S=	0.3889	0.4026	0.4203	0.4378	0.4524	0.4643	0.4752	0.4858	0.4967	0.5086	0.5211
TIME = 21.168 S.	DEPTH	M=	0.0221	0.0236	0.0255	0.0274	0.0290	0.0304	0.0317	0.0330	0.0343	0.0358	0.0373
	VELOCITY	M/S=	0.1560	0.1311	0.1033	0.0822	0.0717	0.0685	0.0685	0.0694	0.0699	0.0698	0.0693
	FLOW RATE	L/S=	0.2005	0.1851	0.1631	0.1437	0.1357	0.1382	0.1464	0.1567	0.1666	0.1763	0.1852
	WAVE SPD.	M/S=	0.3960	0.4039	0.4216	0.4384	0.4524	0.4640	0.4747	0.4854	0.4965	0.5083	0.5208
TIME = 21.447 S.	DEPTH	M=	0.0222	0.0237	0.0256	0.0275	0.0290	0.0304	0.0316	0.0329	0.0343	0.0357	0.0373
	VELOCITY	M/S=	0.1546	0.1292	0.1018	0.0822	0.0723	0.0700	0.0700	0.0705	0.0706	0.0700	0.0690
	FLOW RATE	L/S=	0.2000	0.1841	0.1619	0.1441	0.1370	0.1411	0.1493	0.1589	0.1682	0.1766	0.1843
	WAVE SPD.	M/S=	0.3969	0.4053	0.4227	0.4339	0.4523	0.4636	0.4742	0.4849	0.4961	0.5079	0.5204
TIME = 21.725 S.	DEPTH	M=	0.0223	0.0239	0.0258	0.0275	0.0290	0.0303	0.0316	0.0329	0.0342	0.0357	0.0373
	VELOCITY	M/S=	0.1535	0.1274	0.1007	0.0825	0.0741	0.0716	0.0715	0.0716	0.0713	0.0703	0.0688
	FLOW RATE	L/S=	0.2003	0.1830	0.1612	0.1450	0.1402	0.1440	0.1520	0.1611	0.1695	0.1769	0.1836
	WAVE SPD.	M/S=	0.3921	0.4067	0.4238	0.4394	0.4522	0.4633	0.4738	0.4845	0.4958	0.5077	0.5202
TIME = 22.004 S.	DEPTH	M=	0.0224	0.0240	0.0259	0.0276	0.0290	0.0303	0.0315	0.0328	0.0342	0.0357	0.0372
	VELOCITY	M/S=	0.1524	0.1257	0.0999	0.0831	0.0755	0.0732	0.0729	0.0727	0.0719	0.0705	0.0687
	FLOW RATE	L/S=	0.2003	0.1823	0.1609	0.1463	0.1427	0.1470	0.1548	0.1631	0.1707	0.1772	0.1830
	WAVE SPD.	M/S=	0.3932	0.4080	0.4248	0.4397	0.4521	0.4629	0.4734	0.4842	0.4955	0.5074	0.5199
TIME = 22.292 S.	DEPTH	M=	0.0225	0.0241	0.0260	0.0276	0.0290	0.0302	0.0315	0.0328	0.0342	0.0357	0.0372
	VELOCITY	M/S=	0.1510	0.1243	0.0994	0.0839	0.0770	0.0748	0.0743	0.0737	0.0725	0.0707	0.0685
	FLOW RATE	L/S=	0.2001	0.1817	0.1610	0.1480	0.1455	0.1500	0.1574	0.1652	0.1719	0.1776	0.1825
	WAVE SPD.	M/S=	0.3944	0.4093	0.4257	0.4400	0.4517	0.4626	0.4731	0.4839	0.4952	0.5072	0.5198
TIME = 22.561 S.	DEPTH	M=	0.0226	0.0243	0.0261	0.0276	0.0290	0.0302	0.0315	0.0328	0.0342	0.0356	0.0372
	VELOCITY	M/S=	0.1496	0.1230	0.0992	0.0849	0.0786	0.0765	0.0756	0.0747	0.0731	0.0709	0.0684
	FLOW RATE	L/S=	0.1997	0.1812	0.1615	0.1500	0.1484	0.1530	0.1600	0.1671	0.1731	0.1779	0.1821
	WAVE SPD.	M/S=	0.3955	0.4106	0.4265	0.4402	0.4518	0.4623	0.4728	0.4836	0.4950	0.5071	0.5196
TIME = 22.840 S.	DEPTH	M=	0.0228	0.0244	0.0261	0.0276	0.0289	0.0302	0.0314	0.0327	0.0341	0.0356	0.0372
	VELOCITY	M/S=	0.1486	0.1218	0.0993	0.0861	0.0803	0.0781	0.0770	0.0756	0.0736	0.0711	0.0683
	FLOW RATE	L/S=	0.2005	0.1809	0.1624	0.1522	0.1514	0.1560	0.1626	0.1690	0.1742	0.1783	0.1817
	WAVE SPD.	M/S=	0.3969	0.4119	0.4272	0.4404	0.4516	0.4620	0.4725	0.4834	0.4949	0.5069	0.5195
TIME = 23.118 S.	DEPTH	M=	0.0229	0.0245	0.0262	0.0277	0.0289	0.0301	0.0314	0.0327	0.0341	0.0356	0.0372
	VELOCITY	M/S=	0.1474	0.1211	0.0997	0.0875	0.0820	0.0797	0.0782	0.0765	0.0741	0.0713	0.0683
	FLOW RATE	L/S=	0.2001	0.1811	0.1636	0.1548	0.1545	0.1590	0.1651	0.1710	0.1753	0.1787	0.1815
	WAVE SPD.	M/S=	0.3980	0.4130	0.4278	0.4405	0.4514	0.4618	0.4722	0.4832	0.4947	0.5068	0.5194
TIME = 23.397 S.	DEPTH	M=	0.0230	0.0247	0.0263	0.0277	0.0289	0.0301	0.0314	0.0327	0.0341	0.0356	0.0372
	VELOCITY	M/S=	0.1461	0.1204	0.1002	0.0889	0.0838	0.0813	0.0795	0.0773	0.0746	0.0715	0.0682
	FLOW RATE	L/S=	0.1998	0.1814	0.1651	0.1575	0.1577	0.1620	0.1675	0.1725	0.1764	0.1791	0.1813
	WAVE SPD.	M/S=	0.3991	0.4140	0.4284	0.4406	0.4513	0.4615	0.4720	0.4830	0.4946	0.5067	0.5193

TIME = 23.675 S.	DEPTH	M=	0.0232	0.0248	0.0263	0.0277	0.0289	0.0301	0.0313	0.0327	0.0341	0.0356	0.0371
	VELOCITY	M/S=	0.1449	0.1199	0.1010	0.0905	0.0856	0.0829	0.0807	0.0781	0.0751	0.0716	0.0682
	FLOW RATE	L/S=	0.1956	0.1818	0.1669	0.1604	0.1609	0.1659	0.1679	0.1742	0.1774	0.1795	0.1811
	WAVE SPD.	M/S=	0.4003	0.4150	0.4289	0.4407	0.4512	0.4613	0.4718	0.4829	0.4945	0.5067	0.5193
TIME = 23.954 S.	DEPTH	M=	0.0233	0.0249	0.0264	0.0277	0.0289	0.0301	0.0313	0.0327	0.0341	0.0356	0.0371
	VELOCITY	M/S=	0.1438	0.1196	0.1020	0.0922	0.0874	0.0845	0.0819	0.0799	0.0755	0.0718	0.0682
	FLOW RATE	L/S=	0.1996	0.1823	0.1669	0.1634	0.1642	0.1679	0.1722	0.1759	0.1784	0.1800	0.1811
	WAVE SPD.	M/S=	0.4014	0.4159	0.4293	0.4405	0.4510	0.4611	0.4716	0.4828	0.4945	0.5067	0.5192
TIME = 24.232 S.	DEPTH	M=	0.0234	0.0250	0.0264	0.0277	0.0289	0.0301	0.0313	0.0326	0.0341	0.0356	0.0371
	VELOCITY	M/S=	0.1430	0.1195	0.1031	0.0939	0.0891	0.0860	0.0830	0.0797	0.0759	0.0720	0.0682
	FLOW RATE	L/S=	0.1999	0.1831	0.1710	0.1665	0.1674	0.1708	0.1745	0.1775	0.1794	0.1805	0.1911
	WAVE SPD.	M/S=	0.4025	0.4167	0.4297	0.4400	0.4509	0.4610	0.4715	0.4827	0.4944	0.5067	0.5192
TIME = 24.511 S.	DEPTH	M=	0.0235	0.0250	0.0265	0.0277	0.0289	0.0300	0.0313	0.0326	0.0341	0.0356	0.0371
	VELOCITY	M/S=	0.1423	0.1196	0.1042	0.0957	0.0909	0.0875	0.0841	0.0804	0.0764	0.0722	0.0682
	FLOW RATE	L/S=	0.2005	0.1842	0.1733	0.1697	0.1707	0.1737	0.1758	0.1771	0.1804	0.1809	0.1811
	WAVE SPD.	M/S=	0.4036	0.4174	0.4300	0.4408	0.4508	0.4609	0.4714	0.4826	0.4944	0.5067	0.5192
TIME = 24.789 S.	DEPTH	M=	0.0236	0.0251	0.0265	0.0277	0.0288	0.0300	0.0313	0.0326	0.0341	0.0356	0.0372
	VELOCITY	M/S=	0.1414	0.1200	0.1055	0.0975	0.0927	0.0890	0.0852	0.0811	0.0768	0.0724	0.0682
	FLOW RATE	L/S=	0.2003	0.1855	0.1758	0.1728	0.1739	0.1765	0.1790	0.1807	0.1814	0.1815	0.1812
	WAVE SPD.	M/S=	0.4045	0.4181	0.4303	0.4408	0.4507	0.4608	0.4714	0.4826	0.4945	0.5067	0.5193

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10. SUPPLEMENTARY NOTES

[X] Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The application of the numerical method of characteristics to the solution of the differential equations defining unsteady flow in partially filled drainage system sized pipes is outlined.

The derivation of the flow equations is presented, together with the necessary boundary equation formulation to represent variable inflow, system discharge and leakage flow past a stationary deposited solid.

A computer program, written in Fortran, is included, together with typical output, that establishes the applicability of this computational method to unsteady flow analysis in gravity flow drainage systems.

Proposals for the extension of the described techniques to the prediction of solid transport and flow attenuation in long pipes are also presented.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

building drainage; numerical solutions for transient depth; unsteady partially-filled pipe flow; waste solid transport.

13. AVAILABILITY

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